Tentative Correlation Between CIPW Normin *pl* (Total Plagioclase) and Los Angeles Wear in Precambrian Midcontinental Granites—Examples from Missouri and Oklahoma, with Applications and Limitations for Use

Chapter G of

Contributions to Industrial-Minerals Research

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U.S. Department of the Interior
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Tentative Correlation Between CIPW Normin *pl* (Total Plagioclase) and Los Angeles Wear in Precambrian Midcontinental Granites—Examples from Missouri and Oklahoma, with Applications and Limitations for Use

By George H. Davis[1]

Abstract

The normative chemical classification of Cross, Iddings, Pirsson, and Washington (CIPW) is commonly used in igneous petrology to distinguish igneous rocks by comparing their magmatic chemistries for similar and dissimilar components. A potential use for this classification other than in petrologic studies is in the rapid assessment of aggregate sources, possibly leading to an economic advantage for an aggregate producer or user, by providing the opportunity to determine whether further physical testing of an aggregate is warranted before its use in asphalt or concrete pavement. However, the CIPW classification currently should not be substituted for the physical testing required in specifications by State departments of transportation. Demands for physical testing of aggregates have increased nationally as users seek to maximize the quality of the aggregate they purchase for their pavements. Concrete pavements are being laid with increased thicknesses to withstand increasing highway loads. New pavement mixes, most notably Superior Performance Asphalt Pavement ("Superpave"), are designed for additional service life. For both concrete and asphalt, the intent is to generate a durable pavement with a longer service life that should decrease overall life-cycle costs.

Numerous aggregate producers possess chemical-composition data available for examination to answer questions from the potential user. State geological surveys also possess chemical-composition data for stone sources. Paired with the results of physical testing, chemical- composition data provide indicative information about stone durability and aggregate strength. The Missouri Department of Transportation has noted a possible relation among coarse-grained Precambrian granites of the midcontinental region, correlating the results of abrasion testing with the contents of normative minerals, also known as normins, calculated from chemical-composition data. Thus, normin *pl* (total plagioclase) can predict, by way of simple regression, the Los Angeles wear for granite samples collected in Missouri. The results of this abrasion testing were extended to another granite in Oklahoma where normin *pl* predicted Los Angeles wear to within 0.6 percent. This relation may also exist for granitic rocks outside the Oklahoma-Missouri region, as well as for other igneous-rock types.

Statement of the Problem

Physical testing is commonly used to characterize aggregate before an engineer specifies it for use. However, screening tests, such as for water absorption and specific gravity, do not immediately identify potential deficiencies that would justify further testing. At present, a single test is not available to determine the potential chemical and mineralogic deficiencies of coarse aggregate. Additionally, problems of costs and reproducibility of results arise for aggregate producers. Those results obtained by an independent testing laboratory or by a producer's laboratory may be inaccurate, causing misinterpretations that lead to unjustified acceptance or rejection of a coarse aggregate. In some circumstances, costs dictate the number and types of tests run to characterize an aggregate. Upon opening a new quarry the producer needs to know how many tests are needed to accurately characterize an aggregate. During the characterization of stone for both aggregate and monument purposes, chemical analysis also is commonly used. The relations discerned during exploration and characterization of potential aggregate materials may be useful in determining the overall value of the stone for a particular use. To maintain quality assurance, these tests must be repeated periodically upon entering new areas or faces of the quarry.

[1]Missouri Department of Transportation, Jefferson City, Mo.

Reproducibility of test results between different laboratories is an issue that emerges for both producers and independent testing laboratories. Although the producer will attempt to ensure the honesty of test results, the use of different technicians or laboratories can cause bias. Legal liabilities to the producer for inaccuracy or inadvertent misrepresentation may also cause bias in test results. Changes of interpretation in the standard procedures used, differences in equipment, and the use of older or outdated equipment also may cause inaccuracy or loss of precision in testing.

Chemical analysis is generally more accurate and precise than physical testing. Chemical properties are known to vary within set limits identifiable before testing. The range of accuracy for a single laboratory test is also known. Two tests with similar results that have an accuracy limit can be compared. If the results of both tests fall within this accuracy limit, then the tests can be increasingly considered valid. The results of accurate and precise chemical analysis can be tentatively correlated with those of simple physical testing at a higher degree of certainty.

Problems of costs, limits of reproducibility and accuracy, bias in test results, and varying degrees of precision represent problems for most producers as they present their aggregate product to potential buyers (including and especially State departments of transportation). Additional rapid, inexpensive, and accurate testing methods and correlations between testing methods can be potential solutions to these problems. Correlations of the results of chemical analysis with those of physical testing may offer an additional tool to the producer or buyer of aggregate because laboratory data are available from many State geological surveys and other sources, particularly university theses. These data may provide a rapid screening tool in the choice of aggregate source and can be used in the selection of new or expanded areas of quarrying or in the choice of aggregate between comparable sources.

Previous Work

Several workers have reported correlations of the results of chemical or mineralogic analysis with those of physical testing. Tugrul and Zarif (1999) reported that the influence of textural characteristics of a stone appear to be more important than its mineralogy in comparisons of engineering characteristics. They used thin-section petrography to identify the mineralogy of the rocks chosen for study, and then tested representative samples for specific gravity, dry and saturated unit weight, water absorption, effective and total porosity, sonic velocity, Schmidt hardness, point-load-strength index, uniaxial compressive strength, and modulus of elasticity. Their correlations were characterized by simple regression analysis, determining that the types of grain contact, grain (mineral) shape, and grain size significantly influenced the physical properties of granitic rock. Although the parameters listed influence the selection of granitic aggregate, they do not effectively characterize rocks for a single end use, such as road aggregate.

Dossey and others (1990) reported on the use of chemical analysis to quickly estimate preliminary concrete properties versus age before comprehensive sampling and testing. Their report was later integrated into an overall procedure for the classification of coarse aggregates (Peapully and others, 1994), based on properties affecting pavement performance. Regression models were developed to predict 28-day concrete properties from the chemical compositions of the coarse aggregate used in the concrete. Concrete mixes were formulated to simulate field conditions, using type I cement, and were allowed to cure at 75°F and 40-percent relative humidity. They used 20 different types of aggregate, including granite, characterizing them chemically by X-ray-diffraction, fusion, and coulometric techniques. The physical properties measured were compressive strength, tensile strength, modulus of elasticity, and shrinkage on drying. Upon completion of the tests, correlation analysis was performed by using Pearson product-moment correlation to determine the degree of dependence or interdependence of the individual chemical components of the aggregates. Because only one granite sample was analyzed, conclusions cannot be drawn at any level of certainty. Regardless of an insufficient sample population, the overall study exhibited a good agreement between predicted and measured modulus of elasticity for portland-cement concrete made from granite.

Needs of a Major Department of Transportation

The Missouri Department of Transportation manages the sixth-largest highway system and the seventh-largest number of bridges in the United States. Critical to programs of construction and maintenance is a reliable supply of quality asphalt and concrete. Limestone, dolomite, rhyolite, and granite are available for concrete and aggregate formulation from quarries located throughout the State.

Missouri's limestone and dolomite producers normally supply aggregate for concrete pavements, which are installed initially on almost all of the State's primary roads. Pavement thicknesses have been increased from 10 in. (25 cm) to 12 in. (30 cm) in the past 10 years, in response to increasing truck weights. Increasing labor and installation costs during construction have caused prices to rise in the past 5 years from approximately $1 million to more than $1.5 million per roadway mile. Pavement failures due to repeated freeze-thaw in cycles have occurred in some areas of the State. Asphalt has become a more cost effective means of rehabilitating older pavements concomitantly. Some roads are rehabilitated by using 1 to 4 in. (2.5–10 cm) of asphalt overlaid on the original concrete, which has been scarified to provide a better binding surface. Some roads are also built by using new Superior Performance Asphalt Pavement ("Superpave") mixes and technology.

Recently, in an effort to supply additional aggregate sources for concrete needs, some producers with quarries in igneous rocks have submitted their stone for approval to the Missouri Department of Transportation. Freeze-thaw testing, testing for potential alkali-silica reactivity, and the new micro-

Deval tests have all been used to further characterize the stone (Wu and others, 1998).

Aggregate Needs for Asphalt Pavement

To be considered for use in asphalt pavement, an aggregate must possess both durability and strength. The aggregate must also have fresh, angular faces and some degree of absorption for the asphalt-binding agent to adhere to it, in order to prevent the binder from stripping from aggregate faces and causing premature failure. Smooth, fractured aggregate faces are not adhered to as well as hackly fractured faces; flattened and elongated aggregate grains are avoided in asphalt mixes also.

Fresh, angular aggregate faces are also more desirable than rounded grains for the added shear strength they provide. When a mass of aggregate is overloaded, a shear plane forms, and aggregate particles tend to slide or "shear" with respect to each other, resulting in permanent pavement deformation. Aggregate shear strength is critically important in all hot-mix asphalt because it provides the pavement's primary resistance to rutting (Asphalt Institute, 1995).

Granites provide excellent asphalt-aggregate raw material. Granites crushed for an aggregate product possess irregular fractured faces and are durable as a result of their inherent strength. When crushed and graded, granites serve as an important aggregate source in many areas of the United States where quality limestones or dolomites are not immediately or economically available.

Aggregate Needs for Concrete Pavement

Most of Missouri's primary and interstate highways are paved with portland-cement concrete. Granite is not normally used in concrete pavements in Missouri, although both the Missouri Department of Transportation and aggregate suppliers are exploring its utility. A potential problem of particular interest with the use of granite in concrete is alkali-silica reactivity between the granite and the cement paste. In granites, silica occurring as quartz is impermeable and reacts only on the surface of mineral grains, where individual Si-O bonds are broken at the molecular level. Because the surface area per unit volume of crystalline quartz is low, the potential for alkali-silica reactivity is also low. However, crystalline quartz that has been transformed by heat and pressure may have a large amount of mechanical strain energy stored in its crystalline lattice (fig. 1). The presence of this higher energy level may make the quartz more likely to be reactive by way of alkali-silica reactivity, although the reaction rate is typically much lower than for aggregates composed of amorphous or finely crystalline silica, such as chert or rhyolite.

Management of potential alkali-silica reactivity is a goal to be attained before installation of a pavement, such as by use of a low-alkali cement, a nonreactive aggregate, or a siliceous mineral admixture, or pozzolan, in the cement. Under most circumstances, these measures are both feasible and economical in the overall cost of the cement.

Physical, Chemical, and Petrographic Testing of Aggregate

In Missouri, physical testing is routinely used to determine the overall acceptability of an aggregate for use. Two levels of approval are granted. First, a producer attains a preliminary approval after certain screening requirements have been met at the highway-district level and at the general-headquarters levels. These screening requirements include a requisite amount of physical testing to indicate the overall general characteristics of the stone being submitted for use in State highways. In addition, the stone is examined at the source by the district geologist to determine its stratigraphy and its overall acceptability for a particular use. The normal screening tests used to determine initial acceptability are listed in table 1. Note that various gradations of aggregate are also tested from stockpiles at the quarry to determine acceptability for a particular use.

Depending on the results of the initial examination and preliminary screening, further testing is commonly requested to determine the suitability of a particular type of aggregate for a particular use. For example, if a dolomite stone is proposed as the aggregate for a portland-cement-concrete pavement, the source rock is tested for susceptibility to repeated freeze-thaw cycles by using a modification of the 300-cycle American Society for Testing and Materials procedure C666, procedure B. For other aggregates, the testing engineer may request chemical analysis of the stone to determine potential problems of compatibility with cement paste, or petrographic analysis of the stone to determine its mineral contents.

One advantage of the Missouri Department of Transportation's laboratory facilities is the high level of training and experience of its technicians. Technicians perform tests according to

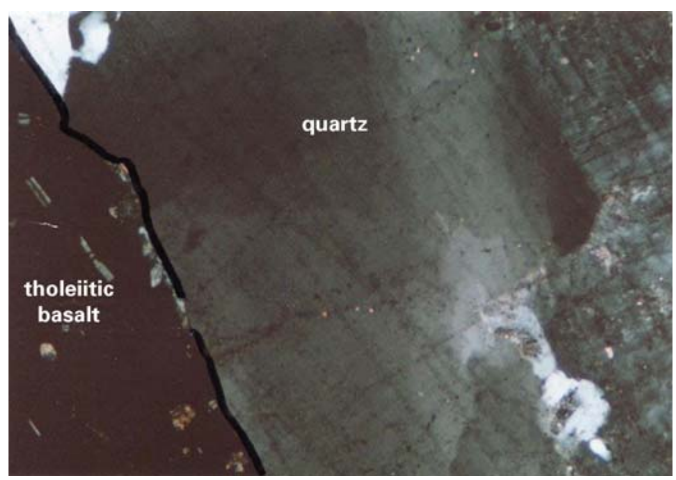

Figure 1. Sample of Troy Granite from Meridian Aggregates' Mill Creek Quarry, Okla., showing undulatory extinction in heat-transformed, or "strained," quartz. Note intrusive tholeiitic basalt to left, outlined in black. Aggregate from this source could be considered potentially alkali-silica reactive. Magnification, 100×. Crossed polars.

Table 1. Screening tests used by the Missouri Department of Transportation for preliminary approval of aggregate.

[AASHTO, American Association of State Highway and Transportation Officials; ASTM, American Society for Testing and Materials]

Test	ASTM specification	AASHTO specification
Specific gravity and absorption of coarse aggregate.	C–127	T–85
Resistance to abrasion (degradation by abrasion and impact) of fine coarse aggregate by use of the Los Angeles machine.	T–104	C–131
Clay lumps and friable particles in aggregate.	T–112	C–142
Flat or elongated particles in coarse aggregate.	None	D4791

the specified procedure and are careful to ensure the integrity of the results. For example, the sieves used to obtain particular aggregate gradations are calibrated versus measurements and standards, temperature requirements are adhered to with strict oversight, and the number of cycles for Los Angeles wear testing is tightly controlled. In this way, high-quality data are obtained that are useful for pavement design and performance prediction.

The present study is an outgrowth of the physical, chemical, and petrographic testing that has been completed at the Missouri Department of Transportation's central laboratory in Jefferson City. After examining data published by the Missouri Geological Survey, trends were noticed that seemed to correlate the results of chemical analysis with those of physical testing. Insufficient samples were available from which to draw meaningful conclusions with confidence, and so further samples were studied during the normal course of physical and chemical testing. The data were augmented with petrographic analysis when requested by the department's engineering staff. The patterns reported here became clearer as additional data were examined. Additional raw data from producers and other State departments of transportation were added to augment the Missouri testing results. Data from a total of 17 samples were obtained, of which 6 were in the original dataset. Eight chemical datasets were derived, along with three additional physical datasets (including one each from the Vermont Department of Transportation and the Arkansas Highway and Transportation Department); three matched pairs of physical and chemical datasets from Luck Stone, Inc., of Virginia; and one chemical dataset from the Arkansas Geologic Commission. In all, 16 of the 19 datasets contained physical and chemical data from which to draw conclusions, and 5 of these 16 datasets contained matching petrographic data.

Quarries and Lithologic Units from Which Testing Results Were Obtained

The lithologic units that were sampled occur in Missouri, Arkansas, Oklahoma, Virginia, Georgia, and Vermont. Missouri rocks sampled and tested include Graniteville Granite, Butler Hill Granite, and Pilot Knob Felsite. Fouche Mountain Nepheline Syenite from Arkansas was tested for inclusion in the data set, and Troy Granite and Tishomingo Granite of Oklahoma were also chemically analyzed.

A chemical analysis of Barre Granite was obtained from Missouri Department of Transportation testing of monument-stone waste rock. Because waste rock from granite quarries is commonly used by State highway-construction projects in asphalt, the Vermont Department of Transportation was contacted to see whether they had any data for correlation with the chemical data; they were cooperative in supplying the Los Angeles wear, water absorption, and specific gravity of the stone. Similarly, physical and chemical data were also obtained from the Elberton Granite Association regarding the Elberton batholith in Georgia.

Previous Superpave projects in the Kansas City area of the Missouri Department of Transportation's District 4 (Kansas City Metropolitan District) had necessitated a trip to Oklahoma to examine rock at Meridian Aggregates' Mill Creek and Snyder Quarries. Although these rocks were never used in Missouri pavements, a complete battery of asphalt tests were completed from which data were available. Thin sectioning of these aggregates was requested to determine the effect of mineralogy on the durability of the stone. Physical, chemical, and petrographic data were available for these two sample locations.

Aggregate from Fouche Mountain Nepheline Syenite of Arkansas was also subjected to physical and chemical testing. Though not a granite, the stone possesses favorable characteristics that allow its use as asphalt-pavement aggregate. Physical data were made available through the courtesy of the Arkansas Geological Commission, and references to additional laboratory-testing results were also obtained, along with petrographic data.

Finally, in the late stages of the present study, physical and chemical data were obtained from Luck Stone, Inc., of Virginia, one of the largest aggregate producers in the United States. Physical test data from their Web site (URL http://www.luckstone.com/crushed/locations/material_prop.php?plantid=19) were supplemented with chemical data from their Burkeville, Boscobel, and Greene Quarries. Information about the sample locations is listed in table 2.

Sample Locations and General Geology

Samples 1 through 6 and 12 through 15 (table 2) are from the Precambrian St. François Mountains area of southeastern Missouri. Samples 1 through 6 were collected and analyzed by the Missouri Geological Survey as part of its effort to characterize the physical and chemical properties of selected stone resources of Missouri (Rueff and Hays, 1991). Samples 12 through 14 were collected in southeastern Missouri with the assistance of Bob Berri of Berri Exploration Services; these samples were analyzed by the Missouri Department of Transportation as examples of the granitic-rock types that

Table 2. Locations of samples used in the present study.

[Do., ditto]

Sample	State	County	Name	Data source
1	Missouri	St. François	DNR #1	Missouri Geological Survey.
2	do	Carter	DNR #2	Do.
3	do	Wayne	DNR #3	Do.
4	do	Iron	DNR #4	Do.
5	do	do	DNR #5	– – –
6	do	St. François	DNR #6	– – –
7	Oklahoma	Johnson	Mill Creek Quarry	Missouri Department of Transportation.
8	do	Jackson	Snyder Quarry	Do.
9	Georgia	Elbert	Elberton	Elberton Granite Association.
10	Vermont	Washington	Barre	Vermont Department of Transportation, Missouri Department of Transportation.
11	Arkansas	Pulaski	Pulaskite	Arkansas Geological Commission.
12	Missouri	St. François	Berri #1	Missouri Department of Transportation.
13	do	do	Berri #2	Do.
14	do	do	Berri #3	Do.
15	do	Iron	Missouri "Red"	Do.
16	Arkansas	Pulaski	Pulaskite "check"	Do.
17	Virginia	Greene	Greene Quarry	Luck Stone, Inc.
18	do	Goochland	Boscobel Quarry	Do.
19	do	Nottoway	Burkeville Quarry	Do.

occur in southeastern Missouri. Sample 15 was submitted for final approval to the Missouri Department of Transportation's central laboratory in Jefferson City in 2002 for possible use as stone in asphalt and concrete. This sample, from the "Missouri Red" Granite Quarry from near Graniteville, Mo., is representative of the Precambrian Graniteville Granite.

The St. François terrane of Missouri consists of a series of volcanically extruded rhyolite flows and plutons and batholithic ring-shaped intrusions of granite and felsite. Granite and rhyolite are exposed on the surface as the result of weathering and erosion. The granite in the terrane is part of the St. François Mountains Intrusive Suite, which also includes diabase and gabbroic dikes and sills. Stocks and plutonic bodies consist of granite, adamellite, syenite, diorite, and some granite porphyry (Tolman and Robertson, 1969; Amos and Desborough, 1970; Kisvarsanyi, 1976, 1981; Berri, 2002).

Samples 7 and 8 are from Meridian Aggregates' Mill Creek and Snyder Quarries in Oklahoma, respectively. Aggregate from the Mill Creek Quarry consists of Precambrian Troy Granite, which has been intruded by a Cambrian tholeiitic diabase. The quarry is notable for the dike swarms that intruded during the same rifting event responsible for the Oklahoma aulacogen. Dikes in the quarry trend approximately N. 60° W., consistent with this Cambrian rifting event. Tishomingo Granite from the Snyder or Long Mountain Quarry includes a graphic granite that tends toward granophyric textures (fig. 2). This textural significance would make it the cupola of a stock or other pluton rather than a dike (Gilbert and Denison, 1998).

The data for sample 9 were obtained from the Elberton Granite Association of Georgia. The monument stone from the Elberton batholith is remarkably homogeneous; the batholith is dated at Precambrian. Although the Elberton Granite Association supplied some physical data, Los Angeles wear was not included.

Sample 10 was obtained from the Rock of Ages Quarry in the Barre Granite of Vermont (fig. 3). This quarry is one of the largest quarries in the world, producing a wide variety of monument and sculpting stones to many users. Waste rock is also used in asphalt pavement by the Vermont Department of Transportation, which provided physical data from its files. The Barre Granite is also dated at Precambrian.

Samples 11 and 16, from the Granite Mountain Quarries near Sweet Home, Ark., were analyzed at the Arkansas Highway and Transportation Department laboratory in Little Rock, Ark., and the Missouri Department of Transportation laboratory in Jefferson City, Mo., respectively. Theoretically, both samples should be the same or nearly so in their physical and chemical properties. This assertion will be further examined in subsequent discussion. Note that the stone from this quarry is not granite but nepheline syenite, as indicated by its whole-rock chemistry and petrography.

Data for samples 17 through 19 were obtained through the courtesy of Luck Stone, Inc., of Richmond, Va. Physical data were obtained from Luck Stone, Inc.'s Web site (URL http://www.luckstone.com/crushed/locations/material prop.php?plantid=19), and chemical data from Bruce Faison (unpub. data, 2003).

Physical Data

Physical data were arrayed in a spreadsheet summarizing the available laboratory-testing results from all sources into a working document from which comparisons could be made. The data included Los Angeles wear, water absorption, specific gravity, and notes about the stone's location or the data source. The data set includes samples from the following stratigraphic units: the Precambrian Graniteville Granite (samples 1–5, 15)and the Precambrian Butler Hill Granite (samples 6, 12) of southeastern Missouri; the Precambrian Troy Granite (sample 7) and the Precambrian Tishomingo Granite (sample 8) of Oklahoma; the Precambrian Elberton Granite of Georgia (sample 9); the Precambrian Barre Granite of Vermont (sample 10); pulaskite, a post-Pennsylvanian nepheline syenite from Arkansas (samples 11, 16); the Pilot Knob Felsite of Missouri, a Precambrian quartz-poor coarse-grained felsite (sample 13); the Precambrian Breadtray Granite of southeastern Missouri (sample 14); tonalite from the Robertson River Formation of Greene County, Va. (sample 17); the Pennsylvanian Petersburg Granite of Boscobel, Va. (sample 18); and Triassic intrusive granitic rock (quartz monzonite) from Burkeville, Va. (sample 19). Samples 12 through 14 were not physically tested, but all three samples were chemically analyzed.

Additional results of magnesium sulfate soundness testing, sodium sulfate soundness testing, and the new micro-Deval test were also available, but data sets were insufficient to warrant comparison or correlation. The physical data for Los Angeles wear, water absorption, and specific gravity of all samples are listed in table 3.

Chemical Data

Chemical data were also arrayed in the form of a spreadsheet. Certain elemental analyses were not present for all data sets, but all analyses included sufficient data from which Cross, Iddings, Pirsson, and Washington (CIPW) (Cross and others, 1902) norms could be calculated. Oxides analyzed were CaO, MgO, SiO_2, Al_2O_3, Fe_2O_3, Na_2O, and K_2O. Although some analyses did not report MnO or TiO_2, this absence was not deemed important because the short form of the CIPW classification adds manganese to iron in the calculation scheme, and Ti content was less that 1.5 weight percent in all reported samples. The chemical analyses are listed in table 4.

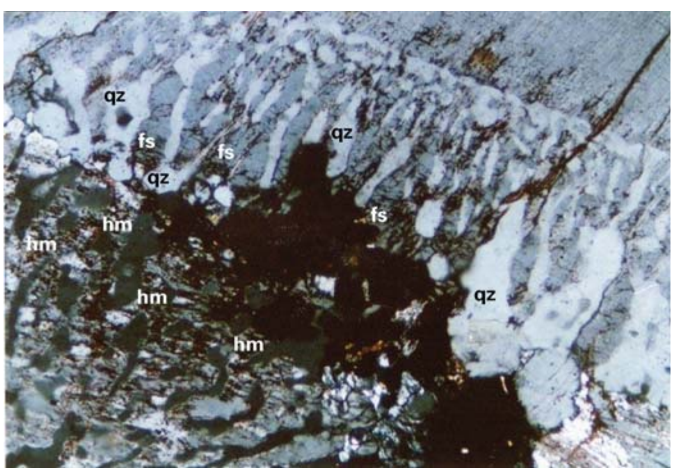

Figure 2. Sample of Tishomingo Granite from Meridian Aggregates' Long Mountain or Snyder Quarry, Jackson County, Okla., showing micrographic or cuneiform texture. Grains of orthoclase feldspar (fs), quartz (qz), and hematite (hm) are clearly visible; opaque grains near center are pyrite. Magnification, 100×. Crossed polars.

Petrographic Data

Petrographic analyses were performed on samples 7 and 8 from the Meridian Aggregates quarries in Oklahoma in Troy and Tishomingo Granite, as requested by the Missouri Department of Transportation in response to questions about the mineralogy of the stone and its potential reactivity in asphalt and concrete pavements. These analyses revealed two different granitic rock types with a similar mineralogy but markedly distinct textural characteristics. Sparse petrographic data from the Granite Mountain Quarries (pulaskite), Luck Stone, Inc. (Burkeville, Va.), and the Elberton Granite Association (Elberton Granite) were also available upon request. A petrographic analysis of Elberton Granite was supplied by the Elberton Granite Association but was insufficient for use. Petrographic analyses of Troy Granite (sample 7) and Tishomingo Granite (sample 8) are listed in table 5.

Petrographic data for pulaskite from Granite Mountain Quarries (Beardsley, 1982) were found to be inadequate for comparison. Producer data from Luck Stone, Inc., for their Burkeville aggregate were also found to be inadequate for comparison.

Some of the petrographic characteristics of Troy Granite and Tishomingo Granite are illustrated in figures 4 through 7. In both rocks, orthoclase, quartz, and plagioclase were the predominant minerals, exhibiting granophyric or cuneiform interlocking textures. Much of the Troy Granite exhibited heat- or pressure-related features from the intrusion of diabase dikes

Figure 3. Rock of Ages Quarry in the Barre Granite, Barre, Vt. Large blocks from this quarry are predominantly used as monument stone and for sculpting; waste rock is crushed to desired grade and used as aggregate in asphalt by the Vermont Department of Transportation.

Table 3. Physical properties of samples determined by laboratory testing.

[See table 2 for sample locations; all samples are from Missouri unless otherwise indicated. NR, not reported]

Sample (table 2)	Los Angeles wear (pct)	Absorption (pct)	Specific gravity	Location and notes
1	13.72	0.89	2.59	Outcrop of Graniteville Granite outcrop near Bismarck.
2	23.52	.62	2.58	Granite from the Van Buren Quarry near Big Spring.
3	11.55	.32	2.62	Granite from the Mill Springs Quarry.
4	20.52	.39	2.6	Granite from the Graniteville Quarry.
5	19.92	.29	2.63	Granite from the Missouri Red Quarry.
6	27.34	.23	2.62	Butler Hill Granite from near Knob Lick.
7	28	1.1	2.65	Mill Creek Quarry, Okla.
8	18	.8	2.58	Snyder Quarry, Okla.
9	NR	.092	2.67	Elberton Granite of Georgia. Data from the Elberton Granite Association.
10	30.6	.8	2.64	Barre Granite of Vermont.Data from the Vermont Department of Transportation.
11	27	.3	2.63	Pulaskite from Arkansas.Data from the Arkansas Highway and Transportation Department.
12	NR	NR	NR	Butler Hill Granite from the Hill O'Mera Quarry.
13	NR	NR	NR	Granite from the Knob Lick Quarry
14	NR	NR	NR	Klondike Hill Quarry.
15	23.54	.5	2.6	Missouri Red Granite.Missouri Department of Transportation check of sample 5 (table 2).
16	27	.4	2.62	Pulaskite from Arkansas. Missouri Department of Transportation check of sample 11 (table 2)
17	32.9	.61	2.8	Luck Stone, Inc., Greene County, Va.
18	28.5	.75	2.6	Luck Stone, Inc., Boscobel Quarry, Va.
19	37.9	.53	2.63	Luck Stone, Inc., Burkeville Quarry, Va.

during the Cambrian rifting event that formed the southern part of the Oklahoma aulacogen (fig. 4). Exposures in the Mill Creek Quarry illustrate the complexity of these intrusions. Fracturing caused by the intrusions also led to the deposition of secondary calcite by meteoric ground water (fig. 5). Accessory minerals in both granites are common (figs. 6–8).

Correlations of the Results of Chemical Analysis with Those of Physical Testing

Dossey and others (1990) described a procedure that correlates the physical data on concrete formulated from particular types of aggregate with the groups of oxides that most commonly cooccur in those types of aggregate. A correlation analysis was run to determine which oxides were independent and which correlated to each other to determine chemical associations, suggesting that the oxides exist naturally together as ores. Their groups were as follows: 1, SiO_2; 2, CaO and CO_2; 3, MgO; 4, Fe_2O_3 and MnO; and 5, Al_2O_3, K_2O, Na_2O, and TiO_2. It was determined that these artificial groupings, though achieving the desired result, did not truly reflect the mineralogy of the stone tested. For example, although lime (CaO) and carbon dioxide (CO_2) appear in group 2 logically as occurring together in calcite ($CaCO_3$), the primary constituent in limestone that was tested, these two oxides appear outside the aggregate-test grouping in other types of aggregate as other minerals. In granite, the lime constituent most likely would be a component of plagioclase, because calcite is rare in most granite, except as a secondary mineral deposited on fracture surfaces. Several other possible discrepancies for igneous rocks also occur in the study, such as the failure to associate alumina (Al_2O_3) and silica (SiO_2), which commonly occur in igneous rocks, because both of these oxides occur in feldspars. Dossey and others (1992) tested only one granite sample, indicating a bias toward limestones and dolomites in their study, and did not adequately address granites and granitic composition, let alone other igneous rocks.

To characterize the possible mineralogic composition of granite and the aggregate used in the present study, a method useful in determining magmatic chemistries, the normative chemical classification of Cross, Iddings, Pirsson, and Washington (Cross and others, 1902) known as CIPW, was chosen. This classification is commonly used to determine the degree of silica saturation in igneous rocks, relating the various amounts of oxides to the known mineralogies that occur in igneous rocks. In this classification, oxides are theoretically recombined to form artificial minerals, or normins, which represent the actual minerals in an igneous rock. Normins may or may not correlate to the actual mineralogy of a sample. The procedure applied by Henderson for achieving silica balance in the normative chemical classification was used (Henderson, 1982). Normins calculated from the chemical analyses completed or reported in table 4 are listed in table 7. The normins are italicized in keeping with current convention. The standard abbreviations for normins are as follows.

Normin	*Abbreviation*
Acmite	*ac*
Albite	*ab*
Anorthite	*an*
Apatite	*ap*
Corundum	*co*
Diaspore	*di*
Enstatite	*en*
Ferrosilite	*fs*
Hematite	*he*
Hypersthene	*hy*
Ilmenite	*il*
Leucite	*lc*
Magnetite	*mt*
Nepheline	*ne*
Olivine	*ol*
Orthoclase	*or*
Plagioclase (total)	*pl*
Quartz	*q*
Wollastonite	*wo*

The data may be arrayed in a suitable format for comparison between individual samples to identify similarities and discriminate discrepancies. Groups of samples may also be arranged from known lithologic units to determine ranges of characteristics, and conclusions drawn from the grouped arrangements. For example, four different samples of Graniteville Granite are compared in table 6. The absence of normins *lc*, *ne*, and *ol* indicates a silica-rich igneous rock. Normin *pl* exceeds normin or in all samples.

Discussion of Results and Limitations of Method

One purpose of the present study was to document any correlations of the results of chemical analysis with those of physical testing and to verify that mineralogy is a control on the quality of aggregate. A potential correlation was observed for Missouri granites whereby an increase in normin *pl* is associated with a corresponding decrease in Los Angeles wear as determined by abrasion testing. This correlation, which was initially recognized in only six samples from Missouri, could be considered only tentative at best. Additional data (table 8) were collected from producers and other sources whereby Los Angeles wear (LAW) can be predicted from normin *pl* by using the regression equation (fig. 9)

$$LAW = -1.02 \times pl + 56. \quad (1)$$

The regression on normin *pl* explains 72 percent of the observed variation (at the 95-percent-confidence level) in LAW, based on data from 13 quarries and sample locations. Equation 1 is likely to be valid for Precambrian granites of the midcontinental region, particularly Oklahoma and Missouri, whereas equations that could be formulated for other regions of the United States are unknown. Of possible concern is a suggestion of heteroscedasticity between normin *pl* and LAW when normin *pl* is greater than 35 volume percent. This relation is shown by the increased scatter of points

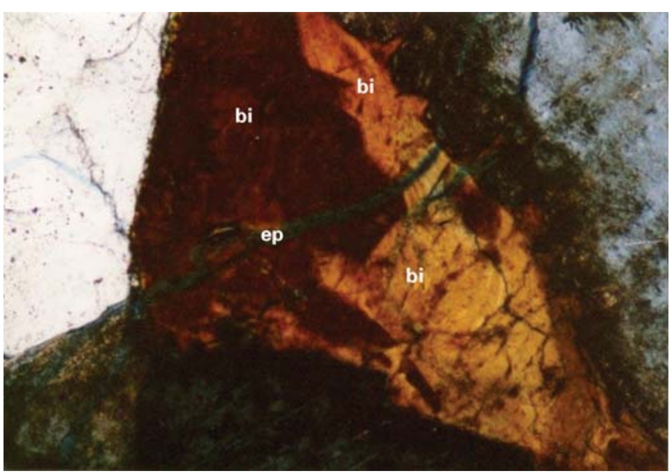

Figure 4. Sample of Troy Granite from Meridian Aggregates' Mill Creek Quarry, Okla., showing undulatory extinction in biotite (bi), indicating stress induced by dike injection. Note epidote (ep) along stress fracture, indicating near-surface weathering. Magnification, 100×. Crossed polars.

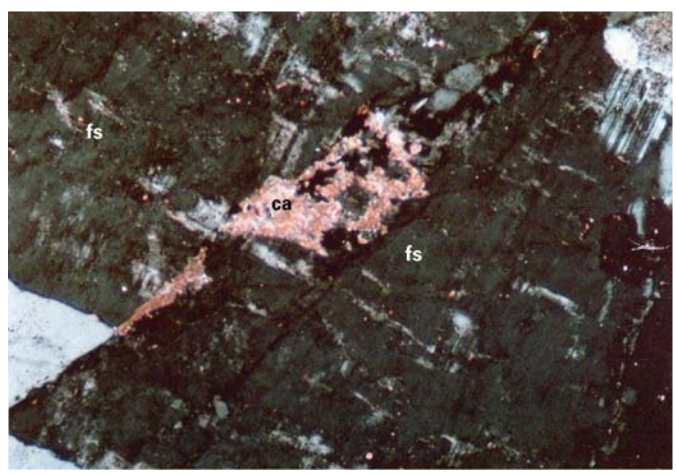

Figure 5. Sample of Troy Granite from Meridian Aggregates' Mill Creek Quarry, Okla., showing calcite (ca) along fracture face in orthoclase feldspar (fs) from dissolution and subsequent reprecipitation by meteoric ground water. Note albite twinning of plagioclase (pl) in upper right corner. Magnification, 100×. Crossed polars.

Table 4. Chemical analyses of samples used in the present study

[All values in weight percent. See table 2 for sample locations. NR, not reported]

Sample (table 2)	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	MnO	Na_2O	K_2O	TiO_2	Total
1	1.05	0.39	69.61	14.36	4.29	0.04	4.49	3.82	0.79	98.84
2	.43	.28	73.19	10.78	3.65	.03	5.47	4.17	NR	98
3	.57	.17	72.94	12.66	4.02	.03	4.03	4.19	.65	99.26
4	.8	.29	73.04	12.38	3.95	.04	3.63	4.28	NR	98.41
5	.73	.06	73.64	12.75	2.77	.02	3.91	4.79	1.39	100.06
6	.37	.06	75.29	11.44	2.44	.01	3.37	4.34	.9	98.22
7	.4	.3	73.54	12.22	3.8	NR	3.31	4.51	.24	98.32
8	.56	.17	72.71	12.73	4.88	NR	3.4	4.76	.23	99.93
9	1.94	.45	69.83	16.56	1.36	NR	4.74	5.03	NR	100.38
10	7.37	.35	66.02	16.06	2.47	NR	2.55	4.37	.43	97.65
11	7.92	.28	61.72	18.88	2.67	NR	3.11	5.15	1.05	100.78
12	6.28	.012	72.26	13.68	1.83	NR	2.14	4.36	.22	100.97
13	7.98	.27	69.61	12.6	3.3	0	2.43	3.34	.4	101.06
14	6.17	.06	72.8	12.21	1.88	NR	2.22	4.2	.18	100.34
15	.67	.04	76.55	12.1	1.55	NR	3.51	4.72	.08	99.22
16	1.27	1.19	60.3	19.93	4.67	NR	6.25	5.3	1.1	100.01
17	3.52	.82	62.07	20.36	7.24	NR	.41	1.5	NR	95.92
18	1.56	.66	71.66	13.18	1.9	.05	3.61	3.95	.23	96.8
19	1.8	.8	72	14	1.8	0.5	3.6	4.6	.3	99.4

about the low end of the regression curve (fig. 9), possibly invalidating the use of regression analysis (Rock, 1988) and suggesting that equation 1 becomes invalid when computed normin *pl* becomes large or simply when the dataset happens to be small. Some possible corrections to this equation can be made, as discussed below.

The correlation of physical properties to CIPW normins is inexact but strongly suggests a correlation between normin *pl* and Los Angeles wear. Several possible corrections to this correlation may be needed, particularly for normin *ap* and perthitic/microperthitic intergrowths. Because normin *ap* contains CaO, which is also a component of normins an and *pl*, a correction may be needed for apatite, indicating a need for P_2O_5 data in the original chemical analysis. It is also strongly suspected that perthitic/microperthitic intergrowths of plagioclase and orthoclase may affect overall stone durability. Such intergrowths may even strengthen the stone.

It is unknown whether the more abundant accessory minerals in granites and other igneous rocks affect these correlations. Some of the more common igneous minerals are not represented in the short form of the CIPW classification used here, including augite, hornblende, muscovite, and biotite, all of which are common in granite. Only biotite and muscovite are common in Missouri granites. In addition, during normin calculation, another relation became apparent as a byproduct of the type of calculation used.

From comparison of the petrographic data on Troy and Tishomingo Granites, Fe in normin *fs* is known to be actually part of the biotite mica present, which is also Fe rich. An orthoferrosilitic composition (>90 volume percent normin *fs*) of hypersthene is rare in nature. Whether these values are misleading, or whether they affect the compositional data and, thus, the comparisons made, is unknown.

The role of petrographic textures in the overall durability of stone has not been determined. Known textures of granites and associated rocks range from porphyritic to granophyric (including myrmakitic, cuneiform, and microtextural analogs of all of the above), and from rapakivi to anti-rapakivi (where orthoclase is surrounded by a reaction rim of albite and conversely, respectively). It is strongly suspected that rocks with textures which allow the interlocking of grains are more durable than those with textures which do not.

The role of the regional geology of granite in its overall durability is also unknown, although strong indications exist

Table 5. Petrographic analyses of samples of Troy Granite and Tishomingo Granite.

Stone	Troy Granite	Tishomingo Granite
Sample (table 2)	7	8
Apatite	Tr	Tr
Biotite	4.0	4.0
Epidote	Tr	Tr
Hematite	3.3	.5
Ilmenite	1.2	.4
Leucoxene	Tr	Tr
Magnetite	.5	– –
Orthoclase	54	– –
Orthoclase+plagioclase (perthite)	– –	61
Plagioclase	2.0	– –
Quartz	35	34
Zircon	Tr	Tr
Total	100	100

Table 6. Comparison of normative-mineral composition of samples of Graniteville Granite.

[All values in volume percent. CIPW, Cross, Iddings, Pirsson, and Washington (Cross and others, 1902). See text for explanation of normin abbreviations]

Sample (table 2)	*il*	*or*	*ab*	*an*	*co*	*mt*	*fs*	*en*	*q*	*hm*	*wo*	*di*	*ac*	*hy*	*lc*	*ne*	*ol*	*pl=ab+an*
1	1.5	22.61	37.94	5.2	0.93	1.25	0.77	0.97	26.15	0	0	0	0	1	0	0	0	43.14
4	0	25.67	28.51	1.83	.52	.72	1.21	.15	37.61	0	0	0	0	1.4	0	0	0	30.34
5	0	28.3	33.06	3.11	0	.81	1.41	.15	30.4	0	0	.4	0	1.1	0	0	0	36.17
15	.15	27.91	29.66	3.3	0	.09	0	.1	36.64	1.18	0	0	0	.1	0	0	0	32.96

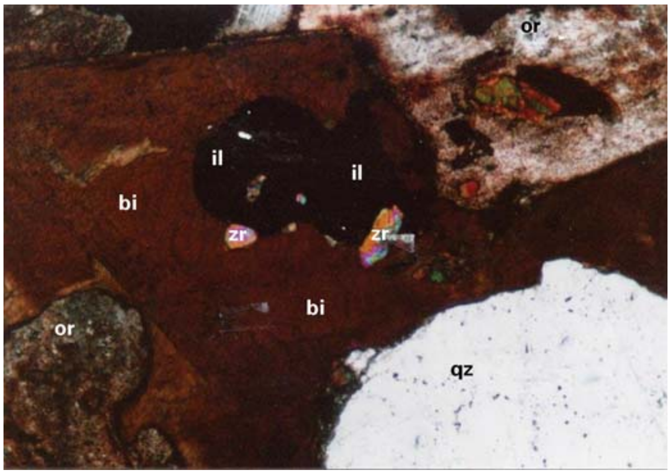

Figure 6. Sample of Troy Granite from Meridian Aggregates' Mill Creek Quarry, Okla., showing opaque ilmenite (il) and zircon (zr) encased by biotite (bi) grain. Orthoclase feldspar (or) in upper right and quartz (qz) in lower right impinge on biotite. Magnification, 100×. Crossed polars.

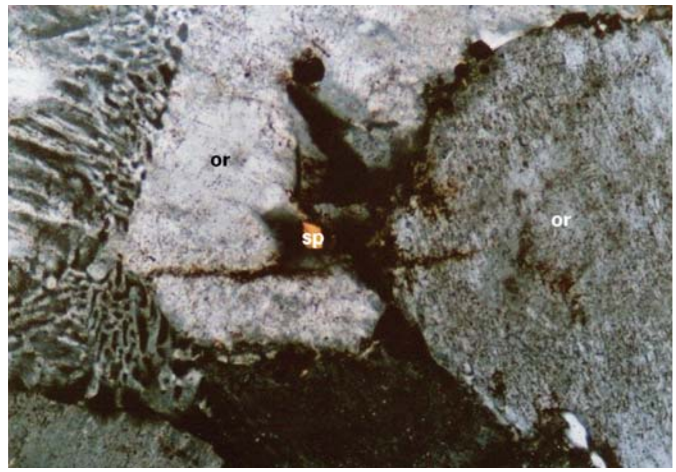

Figure 7. Sample of Tishomingo Granite from Meridian Aggregates' Snyder Quarry, Jackson County, Okla., showing quadrilateral sphene (sp) grain surrounded by orthoclase feldspar (or) with microcuneiform texture. Magnification, 100×. Crossed polars.

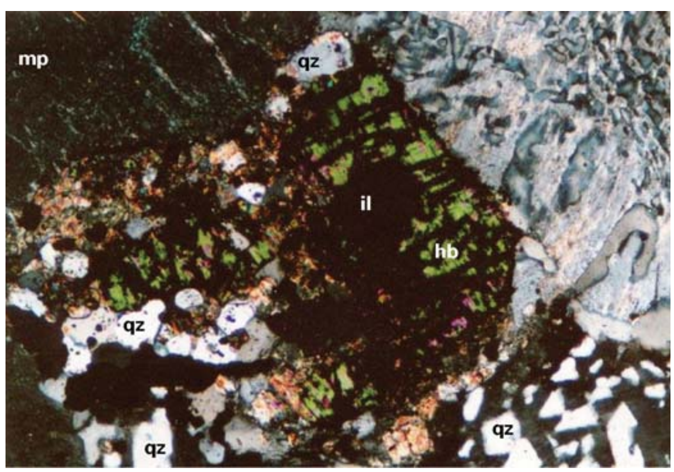

Figure 8. Sample of Tishomingo Granite from Meridian Aggregates' Snyder Quarry, Jackson County, Okla., showing pleochroic hornblende (hb) grain with opaque ilmenite (il), surrounded by cuneiform micrographic quartz (qz) and microperthite (mp). Magnification, 100×. Crossed polars.

Table 7. Normative-mineral composition of samples used in the present study.

Sample (table 2)	*il*	*or*	*ab*	*an*	*co*	*mt*	*fs*	*en*	*q*	*hm*	*wo*	*di*	*ac*	*hy*	*lc*	*ne*	*ol*
1	1.5	22.61	37.94	5.2	.93	1.25	.77	.97	26.15	0	0	0	0	.97	0	0	0
2	0	24.68	32.17	0	0	0	0	.69	28.04	0	.09	1.5	12.38	0	0	0	0
3	1.23	24.79	34.06	2.64	.52	1.16	1.1	.41	31.56	0	0	0	0	1.51	0	0	0
4	0	25.67	28.51	1.83	.52	.72	1.21	.15	37.61	0	0	0	0	1.36	0	0	0
5	0	28.3	33.06	3.11	0	.81	1.41	.15	30.4	0	0	.4	0	1.08	0	0	0
6	1.72	25.29	30.65	3.98	.33	1.14	.47	.92	33.21	0	0	0	0	1.19	0	0	0
7	.48	26.68	27.98	1.97	1.16	1.11	1.49	.74	38.51	0	0	0	0	2.23	0	0	0
8	.44	28.13	28.71	2.78	.97	.74	2.81	.42	32	0	0	0	0	3.23	0	0	0
9	0	29.74	40.09	9.04	0	.39	1.12	.67	18.1	0	0	.47	0	1.56	0	0	0
10	.51	11.2	21.54	26.77	0	.72	.78	.89	30.25	0	2.35	3.39	0	0	0	0	0
11	.99	30.47	26.3	22.26	.06	0	0	0	10.18	.48	6.29	1.5	0	0	0	0	0
12	.41	25.79	18.08	14.82	0	.53	0	0	32.76	0	5.96	1.68	0	0	0	0	0
13	.76	19.77	20.54	13.59	0	.95	0	0	30.55	2.66	9.17	3.3	0	0	0	0	0
14	.35	24.84	20.59	10.93	0	.56	0	0	34.59	0	7.48	1.48	0	0	0	0	0
15	.15	27.91	29.66	3.3	0	.09	0	.1	36.64	1.18	0	0	0	.1	0	0	0
16	2.1	31.35	51.25	6.28	1.6	3.02	0	0	0	0	0	0	0	0	0	.85	4.8
17	0	8.85	3.45	17.43	11.66	2.11	3.58	2.03	43.57	0	0	0	0	5.6	0	0	0
18	.44	23.34	30.5	.41	.41	.56	.64	1.64	31.26	0	0	0	0	2.29	0	0	0
19	.58	27.18	30.44	8.45	0	2.62	1.14	1.99	27.98	0	0	.41	0	2.94	0	0	0

of what particular intrusive-rock types yield the most durable stone. Such rocks as Troy Granite, which has been intruded by other igneous bodies, may have a stronger potential for alkali-silica reactivity, although the interlocking of grains in this granite may actually add to its overall durability.

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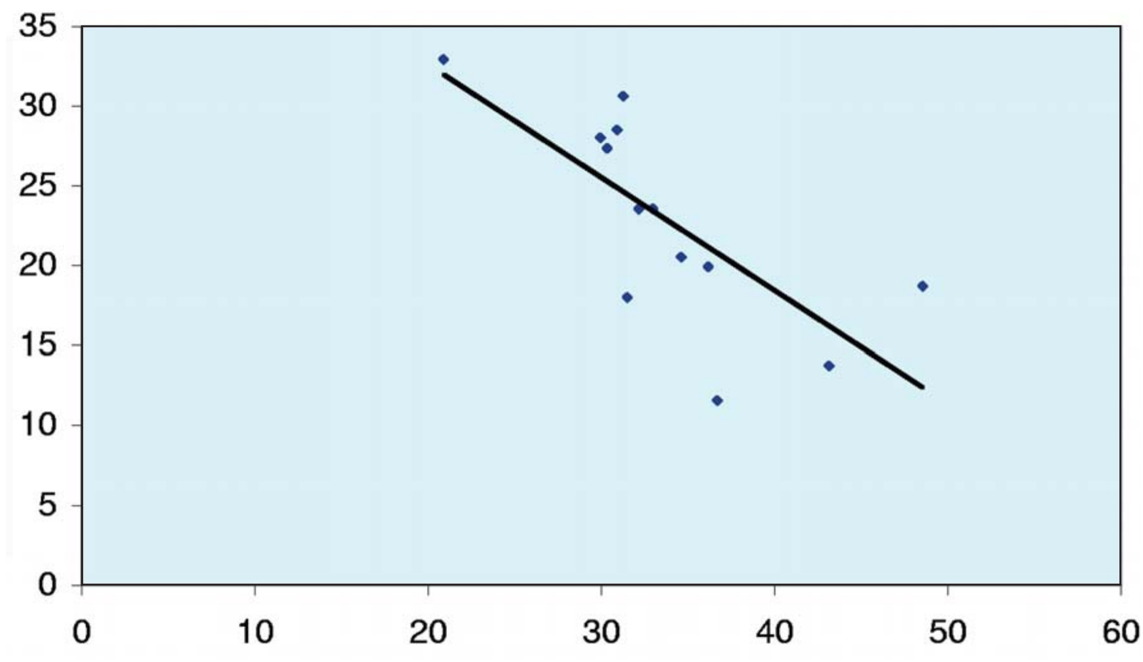

Figure 9. Los Angeles wear versus normin pl. Best-fit curve represents equation 1, using data listed in table 8.

Table 8. Data used in figure 9.

Sample (table 2)	Normin *pl* (vol pct)	Los Angeles wear (pct)
1	43.14	13.72
2	32.17	23.52
3	36.7	11.55
4	30.34	27.34
5	36.17	19.92
6	34.63	20.52
7	29.95	28
8	31.49	18
10	31.27	30.6
11	48.56	18.7
15	32.96	23.54
17	20.88	32.9
18	30.91	28.5

Conversations with Thomas Plymate of the Department of Geology, Geography and Planning of Southwest Missouri State University and with Cheryl Seeger of the Missouri Geological Survey were helpful in improving the ideas presented here.

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