Quality Aggregates for Indiana Highways

K. B. Woods, Director
J. F. McLaughlin, Research Engineer
R. L. Schuster, Research Assistant
Joint Highway Research Project
Purdue University

INTRODUCTION

Until recently aggregates were considered inert materials which, when mixed with some cementing agent, served as filler in concrete. This concept is far from reality. Research and experience have demonstrated that aggregates are physically and chemically active in ways that control their serviceability in concrete. Since these materials constitute about 75 per cent of the volume of the concrete in which they are used, engineers are very interested in the properties of aggregates.

It has been found that certain aggregates contain materials which can have detrimental effects on portland cement concrete. Fortunately, Indiana has an abundance of excellent quality aggregate. Data collected at Purdue show that less than 10 per cent of the aggregate used in Indiana in the last 35 years contained enough of these harmful or "deleterious" materials to produce inferior concrete. However, the use of even this small percentage of inferior aggregates has resulted in considerable consumer loss in terms of shorter life of structures and the necessity of employing more costly designs to offset aggregate weaknesses. Consequently, it is necessary to evaluate the quality of all aggregates before they are used in concrete.

It is the purpose of this paper to review some of the past and current literature related to the evaluation of concrete aggregates and to show how experience, service records, and laboratory research have been combined to produce a background of sound technical information which can be used in the development of specifications for aggregates.

HISTORICAL BACKGROUND

It has long been recognized that certain types of aggregates have harmful effects on the concrete in which they are used (1, 2).[1] It was not until the 1920's, however, that research was begun to determine the quantities of these deleterious constituents that could be included in concrete aggregates. In 1923, Reagel (3) noticed a peculiar surface effect on the concrete pavements constructed in certain localities in Missouri. Portions of the pavement surface 1 to 1½ in. in diameter were cracking loose, and could be pried out or were later displaced by traffic, leaving a hole with sloping sides from ½ inch to 1 inch deep. It was found that, in all cases, a piece of chert[2] was at the bottom of each of these "popouts" and it was evident that the force acting to cause the popout was generated by the piece of chert. As a result of this field study, Reagel conducted laboratory research which showed that the popouts were due to frost action on the concrete containing chert. He concluded that cert should be limited in aggregates to the smallest percentage possible. Later research has shown the same material to be associated with more serious deterioration which results in an overall disintegration and loss in strength.

In 1939, Cantrill and Campbell (6) published the results of a concrete pavement condition survey conducted in Kentucky. Their data showed that serious failures of concrete pavements throughout the western part of Kentucky were due to the use of chert-rich gravels obtained from the Tennessee and Cumberland rivers in the western part of the state. Pavements in which these cherty gravels were used often began to disintegrate within one year after construction.

The results of this survey led Cantrill and Campbell to a laboratory study of the western Kentucky cherts. They found these cherts to be extremely porous, highly absorptive, and possessed of a low specific gravity. When the chert-rich aggregate was incorporated in concrete beams and subjected to 40 cycles of freezing and thawing in water, a definite reduction in flexural strength was noted. It was thus concluded that freezing and thawing was the cause of the disintegration of these lightweight Kentucky cherts when used in concrete pavements.

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[1] Numbers in parentheses refer to the list of references which appears at the end of this report.

[2] Chert may be defined as a dense crypto-crystalline sedimentary rock, composed of chalcedony (microcrystalline fibrous silica and microfibrous amorphous silica or opal) and cryptocrystalline quartz (4). It has a tough splintery to conchoidal fracture. It is commonly white, gray, or blue-gray, but may be brown, black, green, blue, pink, red, or yellow. Flint is a term widely used both as a synonym for chert and as a variety of chert. Tarr (5) states that flint is identical with chert, and recommends that the term be dropped from geologic usage. Although the term flint antedates the term chert, present-day usage favors the latter as the proper designation of the materials to which both terms have been applied (4).

In 1940, Wuerpel and Rexford (7) collected samples of cherty gravel from ten areas in the southern, central and eastern portions of the United States. These samples were separated into four bulk specific gravity groups: 2.50 plus, 2.40 to 2.50, 2.30 to 2.40 and 2.30 minus. Material in each group was analyzed microscopically and tested for absorptive capacity, resistance to frost action, and resistance to the magnesium sulfate soundness test. The results of these tests showed a definite increase in absorption and decrease in soundness with lower bulk specific gravity of the materials tested. These trends were present for all groups lower in bulk specific gravity than 2.50, but were especially noticeable in the pebbles having a bulk specific gravity of less than 2.40.

These results compared favorably with the results of a performance survey of the exposed concrete structures in the areas from which the gravels had been obtained. A group of 100 roughly conical "popouts," each having a piece of disrupted chert at the apex, was collected from representative structures. In every case, the piece of chert had an absorption greater than 4 per cent and a bulk specific gravity less than 2.40.

Beginning in the early 1940's, the deleterious substances in Indiana's aggregates were exposed to intensive study. In 1942, Sweet and Woods (8) published the results of their comprehensive investigation of chert in Indiana's aggregates. They recognized the fact that not all cherts are unsound, and attempted to find a means of differentiating between durable and nondurable varieties. They considered unsound aggregates to be those which are unable to resist excessively large or permanent changes in volume when subjected to destructive agencies, particularly freezing and thawing, heating and cooling, or wetting and drying.

The results of the study conducted by Sweet and Woods made it possible to obtain a correlation between the bulk specific gravity, saturated surface-dry, of a piece of chert, and its performance in the freezing and thawing test. These results showed that the average bulk specific gravity, saturated surface-dry, of unsound chert was lower than that of durable chert. It was found that an upper limit of 2.30 detected entirely unsatisfactory material; *2.45 detected almost all the very harmful types, and included little durable material;* a limit of 2.50 included almost all the nondurable material and also a somewhat larger amount of relatively durable materials than the 2.45 limit.

Venters and Lewis (9) furthered the study of the deleterious constituents of Indiana aggregates by separating large samples of gravels into fractions having different specific gravity ranges and testing these gravels for absorption, degree of saturation, and durability as indicated by the freezing and thawing test. The freezing and thawing test was conducted on 3-by-4-by-16-inch concrete beams in which different aggregate fractions were used.

The results of these tests showed that the aggregates with low specific gravities were characterized by high absorptions, high degrees of saturation, and poor durability in concrete subjected to freezing and thawing. The deleterious substances in the low-specific-gravity fractions consisted mainly of cherts and sandstones. The poor freeze-thaw durability of concrete made with the low-specific-gravity aggregates was of great importance because Venters and Lewis found that the gravels which had low specific gravities also had poor field performance records.

Walker and McLaughlin (10) experimented further with combinations of Indiana aggregates. They found that removal of the low-specific-gravity fractions from gravel aggregates resulted in a concrete of higher durability than that made from the original, unseparated aggregate. They also found that the durability of concrete made with gravel aggregates alone compared favorably with the field performance of the aggregates, thus indicating the validity of the results of the freezing and thawing test.

FIELD PERFORMANCE OF CONCRETE CONTAINING QUESTIONABLE AGGREGATES

Studies have been conducted in several states attempting to relate the field performance of concrete to the type of aggregate employed.

In the 1931 Proceedings of the Highway Research Board, McCown (11) included summary reports from various state highway departments covering a committee report on "The Significance of Sodium Sulfate and Freezing and Thawing Tests of Mineral Aggregates." Included was information from Iowa reporting rather severe deterioration of certain portland cement concrete structures and indicating the cause of the failure was the use of an argillaceous limestone in the concrete. In the same report, similar experiences were presented relating to the use of argillaceous limestone as concrete aggregate in Pennsylvania.

In 1938, Gibson (12) presented data from an extensive performance study of concrete structures in which were incorporated sand and gravel from the Arkansas, Platte, and Kaw Rivers. He found that the predominantly siliceous sands and gravels of the Platte River had caused considerable distress when used in pavements in Missouri, Kansas, and Nebraska.

As previously mentioned, in 1939 Cantrill and Campbell (6) published the results of their condition survey of the 1,100 miles of concrete pavement in Kentucky. This investigation indicated that failure and disintegration of concrete pavement throughout the western part of Kentucky resulted from the use of chert gravel obtained from the Tennessee and Cumberland Rivers.

In the early 1940's, White and Peyton (13) conducted a performance survey of 1,170 miles of concrete pavement in Kansas. The purpose of the survey was to investigate the relationship between certain classes of failure (mainly D-line cracking) and the coarse aggregate incorporated in the concrete. The coarse aggregate consisted of five general types: (a) crushed limestone, (b) chert gravels, sometimes crushed, (c) crushed flint, (d) flint chat, and (e) sand and gravel (mixed aggregate). Predominantly poor records were shown by pavements constructed with Joplin flint, Bazaar gravel (a chert gravel), and the Moline and Kansas City limestones. The Joplin and Bazaar materials undoubtedly failed due to their mineralogic contents. Although no mineralogic analyses were given for the Moline and Kansas City limestones, it is quite possible that the failures of these aggregates were also due to the presence of chert or flint as impurities.

In 1941, Reagel and Gotham (14) published the results of their performance survey of some 450 miles of concrete pavements in Missouri. They were mainly interested in transverse cracking and blowups in the pavements. They concluded that pavements built with coarse aggregate produced from the chert deposits of Missouri tend to develop more transverse cracks and blowups than comparable pavements built with crushed limestone aggregate. Comparisons showed that at five years of age pavements built with limestone had developed 10.5 transverse cracks per 1,000 feet or an average crack interval of 95.2 feet, while comparable chert aggregate pavements had 26.1 cracks per 1,000 feet or a crack interval of only 28.3 feet. This trend persisted for the older pavements also. At 14 years of age the limestone pavements had an average crack interval of 61.3 feet (16.3 cracks per 1,000 feet) whereas the chert pavements had cracks at an average interval of 26.2 feet (38.1 cracks per 1,000 feet). These data show that, on the average, unreinforced pavements, without joints, built with chert aggregates developed in 14 years over twice as many cracks as occurred at the same age in comparable pavements built with limestone aggregates.

Comparison of blowups in pavements built with the two types of aggregates showed an average of one blowup every 4,800 feet for unreinforced pavements made from crushed limestone aggregates, and one blowup for every 1,055 feet of pavement produced from chert aggregates (1.1 blowups per mile versus 5.0 blowups per mile).

In the early 1940s, a comprehensive survey was made of most of the portland cement concrete pavements which were still in use in Indiana. The most important result of this survey was the correlation found between the source of the natural aggregate used in the portland cement concrete and the performance of the completed pavements. This survey, the results of which were published in 1946 by Woods, Sweet, and Shelburne (15), included studies of 3,300 miles of pavement, or about 78 per cent of all the rigid pavements constructed in Indiana between 1921 and 1943. This mileage contained a total of 725 projects, with cements from 17 sources, fine aggregates from 138 sources, and coarse aggregates from 155 sources. Considerable attention was given in this survey to general deterioration and to blowups.

From the results of the study a correlation was established for Indiana pavements between certain sources of coarse aggregate incorporated in the concrete mix and the susceptibility of the resulting pavement to blowups. It was found that 284 miles of pavement (only 10.8 per cent of the total mileage studied) constructed from five sources of supply, contained 1,168 blowups (49 per cent of the total blowups). The crushed stone from one of these five sources was used to construct 97.1 miles of pavement (only 3.7 per cent of the total surveyed) which was found, in this survey, to contain 707 blowups (29.4 per cent of the total blowups). This correlation of blowups with sources of coarse aggregate resulted in the previously unexpected conclusion that expansion joints were not needed in Indiana concrete pavements. On the basis of this work, concrete pavement design was modified in Indiana to omit expansion joints. This has resulted in savings of many millions of dollars.

Although Woods, Sweet, and Shelburne did not perform mineralogical analyses on their aggregate samples, later investigators (16, 17, 18) did analyze gravels from the sources which had resulted in aggregates producing concrete pavements especially susceptible to blowups. These analyses showed that, in most cases, the gravel aggregates with poor performance records contained excessive amounts of chert. The crushed-stone aggregate previously mentioned as having an outstandingly poor record was produced from a dolomitic limestone with an exceptionally low bulk specific gravity and a high water absorption capacity.

The data compiled in this study combined with those of the previously mentioned investigations in other midwestern states make it apparent that the quality of coarse aggregate is an important factor in the resistance of concrete to freezing and thawing. This is further emphasized when it is pointed out that almost all of these coarse aggregates passed the commonly employed acceptance test developed for specification purposes.

In connection with the performance surveys of Indiana concrete pavements, Woods and Gregg (19) found a correlation between pavement performance and texture of the underlying soil. In general they found that pavements underlain by semi-granular and granular materials had better performance records than those underlain by finer materials. The results of the performance surveys showed that many pavements 20 years in age or older and with thicknesses less than the conventional 9-7-9 inches had performed relatively well when located on granular or semi-granular soils. In constrast, many pavements less than 10 years old and of conventional thicknesses performed unsatisfactorily when located on plastic, silty-clay soils. These observations stress the importance of the extensive use of granular materials for embankments, subgrades, and bases.

RELATIONSHIP OF FIELD PERFORMANCE AND LABORATORY RESEARCH

In an effort to determine the reasons for the satisfactory or unsatisfactory pavement performance recorded in the previously cited condition surveys, numerous researchers have attempted to correlate the results of laboratory research with field performance. In Indiana, large-scale chemical and physical laboratory investigations were conducted for this purpose at Purdue University. Several laboratory investigations were undertaken to determine the reasons for the observed field performance and to develop methods for identification of materials which will perform either satisfactorily or poorly.

One of the first of these studies attempting to explain the performance of certain aggregates was conducted by Sweet (20) who obtained samples of stone and gravel with known service records from sources throughout the state, and subjected these aggregates to a complete laboratory research study. Physical properties of each material were determined, including the natural moisture content, void characteristics, microscopic characteristics, and resistance to unconfined freezing and thawing and sodium sulfate tests. Also, the aggregates were incorporated in concrete beams which were subjected to cycles of freezing and thawing.

Because a number of field and laboratory studies had demonstrated the importance of degree of saturation in freezing and thawing tests, this factor was given primary consideration with respect to both the aggregate and mortar components of the concrete.

As a result of Sweet's investigation, it was concluded that Indiana coarse aggregates with poor field performance can be differentiated from those with good performance by means of the freezing and thawing test conducted on concrete test beams made from the aggregate in question. In this particular study, aggregates with good field performance records withstood more than 100 cycles of freezing and thawing in concrete with only about 20 per cent loss in flexural strength, while those with poor performance records sustained about a 50 per cent loss in flexural strength in less than 40 cycles of freezing and thawing.

Sweet's studies also indicated that Indiana aggregates without established field performance records might be evaluated on the basis of their resistance to freezing and thawing tests when incorporated in concrete test beams. He found, however, that when using the freezing and thawing test the aggregate should be incorporated in the concrete in a vacuum-saturated condition in order for the correlation to be valid.

Because the influence of variables, such as the type of freezing and thawing cycle, was not perfectly understood, Sweet suggested that tests should be set up on a comparative basis, comparing laboratory results on beams containing the aggregate in question to results of tests on other materials having established field performance records.

It was also known at that time that a relationship exists between the durability of the concrete aggregate and the pore size distribution and degree of saturation of the aggregate. Sweet investigated this and was able to evaluate these properties in a quantitative manner. He concluded that the volume of pores smaller than 0.005 mm in diameter appears to be a critical index of field durability of Indiana aggregates. This is probably because of the influence of pore size on water-retention and capillary characteristics of the material. He found that aggregates that contained 6 per cent or less of voids having a diameter smaller than the critical diameter of 0.005 mm had good service records while those aggregates having a void volume of 10 per cent or more in the critical size range had poor performance records in concrete pavements.

Venters and Lewis (9) furthered the correlation of laboratory test results with the field performance records of aggregates. They separated Indiana gravels with known service records into fractions having different specific gravity ranges and tested these gravels for absorption, degree of saturation, and durability as indicated by the freezing and thawing test.

The results of these tests showed that aggregates with low specific gravities were characterized by high absorptions, possible high degrees of water saturation, and poor durability in concrete subjected to freezing and thawing. The low-specific-gravity fractions contained greater-than-average percentages of lightweight cherts and sandstones. The poor freeze-thaw durability of concrete made with the low-specific-gravity aggregates was important because Venters and Lewis found that those gravels in this study which had low specific gravities also had poor field records.

As a result of their investigation, Venters and Lewis suggested that increased durability of concrete produced in areas where only inferior aggregates are available could be obtained by the use of field heavy-media-separation processes. They concluded that separation at a specific gravity of 2.40 would improve the durability of poor aggregates considerably and separation at a specific gravity of 2.50 would result in aggregate with good durability.

Walker and McLaughlin (10) experimented further with combinations of Indiana aggregates. They used heavy-liquid separation to obtain various fractions with different minimum specific gravities from gravels with known performance records. They then used these fractions, alone or in combination with good-quality crushed stone, in concrete which was tested for durability in freezing and thawing.

The gravels which were studied all had high chert contents, ranging from 10 to 70 per cent. Although the specific-gravity separation removed other low-specific-gravity materials also, most of the material removed was chert.

Walker and McLaughlin found that removal of the low-specific-gravity fractions from the gravel aggregates resulted in a concrete of higher durability than that made from the original, unseparated aggregate. Also, concrete made with crushed stone-gravel combinations, where the gravel used had a poor service record, was made more durable if some of the lighter specific gravity fractions of the gravel were removed. They also found that the durability of concrete made with gravel aggregates alone compared favorably with the field performance of the aggregates, thus indicating the validity of the results of the freezing and thawing test as a relative indication of the durability of concrete.

SPECIFICATIONS GOVERNING DELETERIOUS SUBSTANCES

The quality of aggregate should be controlled by realistic requirements based on the intended use of the aggregate, and once these requirements have been formulated they should be rigidly adhered to. Aggregate used as a component of concrete produced in Indiana must meet certain rigorous requirements imposed by the climate of this area. Besides possessing those properties necessary for adequate strength of the concrete, concrete aggregates used in Indiana must be resistant to the deterioration caused by freezing and thawing of the concrete. The problem presented to the specifications writer is one of formulating the quantitative requirements which should be imposed in order that only those aggregates which will produce satisfactory concrete are acceptable.

The natural solution to this problem is to base the specifications on research and experience so that requirements are set up which allow the use of only those aggregates which have proven to result in satisfactory concrete both in the laboratory and in the field. The specifications should, however, be drawn so that the best possible use is made of all the available materials. For example, in certain areas of the country there are gravel deposits which, by themselves, are not satisfactory for use in portland cement concrete. It has become common practice in these areas to "sweeten" these gravels by the addition of a good-quality crushed stone thus minimizing the harmful effects of the deleterious substances in the gravels and making them usable. Because most of the common deleterious substances are more harmful in the larger sizes, one would normally want to specify that these materials of lesser quality be restricted to the smaller sizes of the aggregate, let's say all passing the 1-inch sieve.

This has application in Indiana where, in some areas, the gravels are contaminated with lightweight cherts. In this case, crushed limestone is frequently used for the larger sizes of aggregate and the combined material yields concrete having better durability characteristics than the concrete made with the gravel alone.

In addition, aggregate specifications should take into account the character of embankment, subgrade, and base course soils. When these soils are semi-granular to granular, easing of the aggregate specifications might be allowed; when the soils are plastic clays or silty clays, the specifications should be rigidly adhered to.

Finally, there are many uses for aggregates in highways and the requirements or specifications that are imposed should reflect this. For example, although there is good reason to restrict the quantity of lightweight chert in aggregate for portland cement concrete, no such restriction is needed in the case where this aggregate is to be used as a base material.

On the basis of the previously described research, other research, and actual experience with aggregates in service, standard specifications relating to deleterious materials in coarse aggregates for portland cement concrete have been formulated by the American Society for Testing Materials (21) and the American Association of State Highway Officials (22). The portions of these specifications which deal with deleterious materials are shown in Tables I and II. These specifications are typical of those used today by most state highway departments. They are based on experience and performance survey data as well as laboratory data developed throughout the United States. Because these are specifications written by national organizations, they are necessarily broad and cannot deal with specific problems which may exist within a given state. Hence, specifications written by the individual highway agencies may differ from these. In any case, sound, technically constituted specifications are necessary if we are to produce satisfactory concrete capable of long-time performance.

TABLE I

LIMITS FOR DELETERIOUS SUBSTANCES IN COARSE AGGREGATE AS OUTLINED IN ASTM "SPECIFICATIONS FOR CONCRETE AGGREGATES" (C33-55T)

Deleterious Substance	*Maximum, Per Cent by Weight of Total Sample*
Clay lumps	0.25
Soft particles	5.0
Chert that will readily disintegrate (soundness test, five cycles)	1.0
Material finer than No. 200 sieve	1.0[1]
Oven-dry material floating on a liquid having a specific gravity of 2.0	1.0[2]

[1] In the case of crushed aggregates, if the material finer than the No. 200 sieve consists of dust of fracture, essentially free from clay or shale, this percentage may be increased to 1.5.

[2] This requirement does not apply to blast furnace coarse slag.

TABLE II

LIMITS ON DELETERIOUS SUBSTANCES AS OUTLINED IN THE AASHO "STANDARD SPECIFICATIONS FOR COARSE AGGREGATE FOR PORTLAND CEMENT CONCRETE" (M80-51)

Deleterious Substance	*Recommended Permissible Limit, Per Cent by Wt.*	*Maximum Permissible Limit, Per Cent by Wt.*
Soft fragments	2.0	5.0
Coal and lignite	0.25	1.0
Clay lumps	0.25	0.25
Material passing the No. 200 sieve	0.5	1.0
Thin or elongated pieces (length greater than 5 times average thickness	....	15
Other local deleterious substances	As specified	As specified

SUMMARY

On the basis of the information obtained from laboratory research and pavement surveys, the following conclusions may be drawn regarding correlation between the source of coarse aggregate and the performance of portland cement concrete pavements in Indiana:

1. There is a definite correlation between the performance of Indiana pavements and the quality of the aggregate used in them.
2. Indiana aggregates, in general, are of good quality. This is indicated by the fact that about 90 per cent of the 3,300 miles of highway pavements studied by Woods, Sweet, and Shelburne (15) showed only minor distress caused by the coarse aggregate used.
3. The small percentage of Indiana aggregates which are of inferior quality presents a serious problem to both consumer and producer interests in this state. This is particularly true in connection with the development of new sources of aggregate supply. Producers should protect their investments by ascertaining that all proposed workings be in materials of acceptable quality. Consumers should be certain that all aggregates they use are of the proper quality to insure satisfactory performance.
4. On the basis of geologic considerations and the work of researchers in neighboring midwestern states, it is apparent that many of the aggregate materials found to be of inferior quality in Indiana also occur in these other states.
5. Realistic specifications on concrete aggregates are necessary to assure finished products having satisfactory strength and durability. The specifications outlined by the American Society for Testing Materials and the American Association of State Highway Officials are in this category. They are based on performance survey data as well as laboratory data developed throughout the country. Specifications such as these are necessary if we are to produce satisfactory pavements capable of long-time performance.
6. Realistic specifications are also ones which permit the best possible use of all available materials. In the case of aggregates for concrete, "sweetening" inferior gravels, limiting their top size, and using granular base courses to provide drainage are examples of devices which can be employed to permit the use of materials which otherwise might be ruled out on the basis of quality.

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