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THE AGGREGATE THE KEY TO HIGH-PERFORMANCE CONCRETE

By

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ABSTRACT

The aggregate portion of concrete mixtures and mixture production paradigms are discussed starting with work by D. A. Abrams, published in 1918, through projections for the 21st century. Past and current paradigms and the background for the paradigm shift that took place between the mid 1930s and 1970 are described. The reason for “old concrete” outperforming new concrete is explained. A graphic with five zones that can be correlated with combined aggregate grading is provided as a means to evaluate mixtures and project performance. A second paradigm shift, started in 1986, is discussed. It has led to changes in ASTM, ACI, some state DOT, and USAF standards. Premature distress of US Air Force airfields and problem resolution are described and correlated with the current paradigm shift. When needed to support the subject, non-aggregate related matters are mentioned.

Keywords: Aggregate, mixtures, paradigms, standards, durability

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There are conflicting accounts of concrete performance. On the one hand, building industry needs to increase column load carrying capacity have been resolved by producing high-strength concrete. On the other hand, premature deterioration of concrete in the infrastructure is an international problem. The difference in performance has a great deal to do with aggregates. In recognition of performance differences, Shilstone (1) classified concrete based upon projected service environment.

> ***"Active concrete"*** is concrete that will be exposed to water or other aggressive service environment. It must not only meet structural requirements but also be durable based upon such qualities as permeability, *freeze/thaw* resistance, and alkali-silica reactivity.
>
> ***"Passive concrete"*** is concrete subject to only structural toads in a protected environment where it will not be exposed to water. This type of concrete can be evaluated by its minimum strength such as 28-days and possibly shrinkage and creep.

There are no easy tests to measure performance-based requirements for active concrete. Instead of coping with the problem, strength is used as a means to determine quality acceptance for both applications. Though evaluating performance by measuring strength at 28-days satisfies the needs for loading stresses; strength IS NOT a measure of the durability essential for the infrastructure.

Increasing strength through the addition of cement with the intent of improving durability can be counter productive. Improving soundness to improve durability leads to higher strength. While the normal structural strength for active concrete in civil works may be on the order of 3,000 to 4,000 psi, when durability is considered and the mixture is planned to be durable, the strength produced will be between 5,000 and 6,000 psi or more.

Questions are raised about why "old concrete' is out-performing modern concrete. The authors have identified two different aggregate-related mixture proportioning paradigms that answer that question and the importance of a paradigm shift spanning from the mid 1930's to 1970. A 1938 change in aggregate standards had a major, seldom recognized, influence on the shift and concrete performance. The first segment of the shift was slow but the changes in the last decade were very rapid.

While this discussion will be primarily of the aggregate fraction, other factors contributing to the shifts and especially those affecting the current paradigm, will be discussed. They are described in greater detail by Shilstone and Shilstone (2) (3). More recently, Mehta (4) pointed to additional issues.

By common perception, the paste, consisting of portland cement, pozzolanic materials, air-entrained voids, admixtures, and water, is considered by most to be the most important component because its characteristics can be correlated with structural criteria. Though aggregate occupies the most volume in concrete, it is relegated to a secondary function of filling voids to yield the required volume at the lowest price. It is divided into coarse and fine sizes to simplify handling but, by that division, it loses its identity as a single concrete component. This perception of concrete differs widely from that held by the early technologists.

The Early Paradigm

The early paradigm can he traced to Abrams' (5) 1918 research and early materials standards. Abrams' findings are best stated in his own words. Much of his research and recommendations have been neglected and only the water-cement ratio survived. Even the fundamentals of that theory are not interpreted as he apparently intended. He wrote:

"These studies have covered an investigation of the inter-relation of the following factors:

"I. The consistency (quantity of mixing water).
"2. *The size and grading of aggregates.*
"3. The mix (proportion of cement).

"The following may be mentioned as among the most important principles which have been established with reference to the design of concrete mixtures.

"1. With given concrete materials and conditions of test the quantity of mixing water used determines the strength of the concrete so long as the mix is of a workable plasticity.
"2. The sieve analysis famishes the only correct basis for proportioning aggregates in concrete mixtures.
"5. The sieve analysis curve of the aggregate may be widely different inform without exerting any influence on the concrete strength.
"12. There is an intimate relation between the grading of the aggregate and the quantity of water required to produce a workable concrete.
"13. The water content of a concrete mix is best considered in terms of the volume of the cement – the water-ratio."

From the foregoing, Abrams' first concern was to reduce total water through proper blending of the aggregates. Only after the water and aggregate proportions were determined did he introduce the question of cement. This indicates the aggregate should be the first, rather than the last, constituent to be considered when preparing mixture designs or proportions. Today the water and cement are determined first and the aggregate selected to fill the voids. Also, according to Abrams, "aggregate" is an all-inclusive term. There is no separation between coarse and fine sizes. He developed and used a formula, based upon the combined aggregate fineness modulus, to calculate proportions of coarse and fine sizes for the 50,000 tests in the research.

ASTM C33 (6) has long been the standard for aggregate quality though amended and used under AASHTO and state DOT standards. The 1923 version of ASTM C33 included a requirement that was a major influence leading to long-term performance of "old concrete". The statement was: *"The fine aggregate shall preferably be graded from fine to <u>coarse with the coarser particles predominating</u>, within the following limits:* (in percent passing without tolerances) *3/8"- 100%; No 4 sieve - 85%; No. 30 sieve not more than 30%; decantation not more than* 3%.

Coarse aggregate was specified to be finer than today. For example: the ASTM C33, Size 57 (25 mm (1-inch)) tolerance for percent passing the 1/2-inch sieve was 40 to 75% in 1923 while the current standard is 25 to 60%. When coarse aggregate grading approaches current minimum levels, placing and finishing problems develop. Cumulatively, the 1923 coarse and fine aggregate standards assured more aggregate particles in the 3/8" to No. 16 sieve sizes would be included in a mixture than are provided under today's standard. Today, there is a deficiency in aggregate particles retained on the Nos. 4 through 16 sieves creating voids that can be tilted only with fine sand, water, and cement. The result is an increase in stickiness that makes the mixture less responsive to vibration and a decrease in durability due to increased permeability.

The PCA's DESIGN AND CONTROL OF CONCRETE (7) (D&CC), Issue 1, reflected the importance of combined aggregate with such comments as, *"Aggregate is an inert material which is mixed with portland cement and water to produce concrete. This division* (coarse and fine aggregates) *is **largely arbitrary** but should be preserved as a means of maintaining uniformity in grading of successive batches of concrete."* Table II provided typical grading of sand with 65% passing the No. 8 sieve.

The National Sand and Gravel Association and National Ready Mixed Concrete Association (8) researched Abrams' combined fineness modulus formula in 1956. Fine and coarse aggregates were separated by individual sieve size and recombined to produce a combined fineness modulus of 5.25. The coarse aggregate grading was maintained constant for each of 17 different fine aggregate gradings varied to produce the coarsest, finest, and median of ASTM C33 gradings and have a "belly" and a "gap" at each particle size with fineness moduli varying from 2.15 to 3.33. Fine aggregate content varied from 32.7 to 43.4 percent of the total aggregate.

Each mix was cast on each of three consecutive days and results averaged. The cement factor was 293 kg/cum (495 lbs/cuyd). Total water variation was 8.3 liter/cuyd (14 lbs/cuyd) and slump variations were within *75* and 100 cm (3 to 4 inches). The average compressive strengths of one group of three mixtures with water/cement ratios of 0.577, 0.578, and 0.585 were 34, 33, and 32 MpA (4980, 4830, and 4670 psi) respectively. The average strengths of the other 14 mixes with water/cement ratios ranging from *0.555* to 0.570 varied from 34.8 to 37.0 MpA (5060 to 5370 psi). The investigators confirmed Abrams' point 5 (quoted above) finding and reporting that almost any sand grading may be used to produce a given strength but adjustments must be made in proportions as grading varies.

Abrams investigated and commented upon the different methods for aggregate proportioning used at that time. Among the most important ones he identified were:

- Arbitrary, such as the 1:2:4 mix ratio, without reference to the size or grading of the fine and coarse aggregates,
- Blending of aggregates made to secure maximum density.
- Securing maximum concrete density;
- Sieve analysis to approximate some predetermined grading, and
- Surface area of aggregates.

He wrote of those procedures, *"It is a matter of common experience that the method of arbitrary selection in which fixed quantities of fine and coarse aggregates are mixed without regard to the size and grading of the individual materials, is far from satisfactory. Our experiments have shown that the other methods mentioned above are also subject to serious limitations."* The "percent of aggregate" method, the most widely used method today for selecting coarse to fine aggregate proportions due to its simplicity, is a derivation of the 1:2:4 proportioning method. The notorious 60:40 aggregate ratio is a modem day version of 1:3:5 volumetric proportions.

The use of well-graded, combined aggregate mixes in old concrete can he confirmed by examining the eroded surfaces. The predominating material will be found to be *"the coarser particles of sand."* These castings have survived in severe environments, though not air entrained. When cored, such concrete will often produce strengths over *55* MpA (8,000 psi), though the original strength was probably in the range of 10 to 17 MpA (1,500 to 2,500 psi). The aggregate is densely distributed and well graded throughout the mixture with 19 mm (3/4-inch) top size. Figure 1 illustrates the difference in combined aggregate grading reflected in cores from concrete cast in 1929 and 1986.

The First Paradigm Shift: 1935-1970

The shift came about slowly but then grew almost exponentially during the 1960-1970 period. While Mehta (4) suggests other 1930s factors, 1938 was a year of major change from the aggregate point of view. It was in that year that two aggregate related factors coincided. First, Goldbeck / Gray (9) published an aggregate proportioning table under the tide of *"For concrete placed without the use of internal vibration."* Second, the reference in ASTM C33-23 to fine aggregate being predominately coarse articles was deleted and replaced with early versions of the gradings published today. *t*

The Goldbeck / Grey table provided a correlation between the dry rodded unit weight (DRUW) of the coarse aggregate and the fineness modulus (FM) of the fine aggregate. This is in conflict with Abrams because it only marginally considers grading. DRUW is affected by particle shape, texture, and density as well as grading. FM is said to indicate the fineness of the fine aggregate but that is true only for a single source. With each source, the FMs may be the same as other sources but there may be major differences in grading.

The table limited the coarseness of the fine aggregate in an apparent attempt to divide the coarse and fine aggregates at the No. 4 sieve. Coarse sand confused that concept. This process moved the industry away from recognizing the importance of combined aggregate. Since the authors were National Crushed Stone Association engineers, they undoubtedly were members of the ASTM C33 committee. Tbç Goldbeck / Gray table is now the American Concrete Institute standard published in ACI 211(10). It is often found that that table produces over-sanded mixtures that contribute to placement and finishing problems and poor durability for active concrete.

Among the other non aggregate factors affecting concrete quality during the transition period were:

- Increased cost of interim finance for commercial building construction led to changes in cement chemistry and fineness of grind to provide early slab form stripping to accelerate construction. This contributed to major reductions in strength gain after 28-day age (11) (12).

- Practical concrete technology research and assistance to engineering and construction companies was cut-back by the Portland Cement Association when ready mix producers did not favor the cement producers that paid the bill for the service. This severed a major line of technical leadership for the industry. Academic research has not replaced that work.

- Virtual elimination of concrete technology training (13) (14) for engineering students and omission of internship in the field after graduation to learn how to translate academic theory into practical design details and specifications has led to many engineers not understanding the basics of concrete technology. The concrete industry is functioning without the level of engineering materials and concrete construction leadership needed to professionally guide it through major changes in materials, methods, and objectives. The importance of chemical admixtures to facilitate construction needs and yet produce the specified 28-day strength has led to the admixture salesmen being among the most important technical leaders.

- Expanded use of pozzolanic materials and admixtures facilitates construction operations and increases the ease whereby 28-day strength may be achieved to satisfy specification requirements.

- o Almost unquestioned acceptance of concrete based upon 28-day strength regardless of the fact it has little relationship to durability.
- o Unrelenting emphasis on low bid price has resulted in selection and use of aggregates and mixtures that accept minimum standards and poor practices.

The Current Paradigm

Mixture proportioning methods are far outdated for current needs. During construction, the aggregates are allowed to vary within the broad tolerances of accepted standards without mixture adjustments. It is patent that: fixed weights of variable materials assures variable output. Often a water/cement ratio is specified but since it cannot be readily measured in the field, strength is the sole quality verified for acceptance. Water-cement ratio can best be verified by tracking production and delivery of concrete. That was the standard practice in the 40s and 50s. Prior to that time, inspectors verified the addition of water to the site-mixed concrete.

Little attention is paid to the aggregate characteristics once a source is approved. In many cases, aggregate grading data is furnished by the supplier and not verified at the concrete batch plant. While some aggregate producers furnish test results from load-out locations, other data comes from the point of production. The production data may not be valid as it may be segregated when added to stockpiles. Recent QA/QC programs ate changing requiring tests be made at the concrete batch plant. That information should be used to a just proportions and not just indicate “pass – fail.”

In summary, the current concrete paradigm does not fit the national need for high-performance concrete and construction of the nation’s infrastructure.

The Second Paradigm Shift: 1986 - ????

The current transition commenced in 1986 followin~ the release of an IBM PC compatible software program named **seeMIX** (‘visualize a mixture”). The program was designed to assist concrete technologists develop mixture proportions using the traditional methods, analyze and modify that mixture, and make adjustments as materials and statistical history vary during construction. Once mixture proportions are calculated, the program mathematically mixes the concrete and profiles the mixture characteristics using a series of graphics. It soon became apparent that the graphics could be used to describe how a mixture would perform.

Shilstone (15) (16) described the technology based upon research for the U. S. Army Corps of Engineers in 1975 for construction of a $600 million project in Saudi Arabia and results from early use of the software. The Coarseness Factor Chart (Figure 2), as modified in 1996, evolved from the Saudi Arabian research. The “X” axis is the percent of the combined aggregate retained on the No. 8 sieve that is also retained on the 3/8” sieve. The “Y” axis is the percent of the combined aggregate passing the No. 8 sieve with adjustments based upon cementitious materials content.

Two grading charts were included in the software program. One showed the cumulative percent passing each standard sieve. The other identified the percent of the combined aggregate retained on each sieve. The Coarseness Factor Chart and the percent retained chart have become the primary means to evaluate a mixture. Figure 3 is the aggregate particle distribution from two major, widely separated paving projects (both at “**P**,” Figure 2). Such a particle distribution is typically found where there are placing, finishing, cracking, spalling, scaling, edge slough, edge slump, and poor ride. The ‘peak-valley-peak shape is identified with mixtures that are classified as “gap-graded.” This trend was found, though less severe than in Figure 3, for a typical mixture with aggregate complying with the ASTM C33 size 57 coarse aggregate and concrete sand. In that case, only the No. 8 sieve is in a deep “valley. It is not uncommon to find more aggregate retained on the Nos. 50 and 100 sieves than the combined retained on the Nos. 8, 16, and 30 sieves.

At one of the above-illustrated cases, the 1 cm (0.4’) slump mix segregated when dropped from the mixer into dump trucks. Large portions of mortar were expelled from the body of the mix to the sides and corners of the trucks. Two trucks, working in parallel, dumped their loads in the right-of-way ahead of the paver resulting in “jelly lines” in the middle of the pavement and at the edges. Portions of the concrete were not plastic due to high coarse aggregate content. They did not respond well to vibration so a great deal of grinding was needed to meet ride requirements. Edge slump was a common problem. Significant segregation was observed in the second case though placement was by conveyor.

The particle distribution indicated by Figure 4 was suggested in 1986 as a means to overcome the peak-valley and produce a better mixture. This suggestion was widely tested and found valid. When such aggregate gradings were used, water was reduced from 9 to 16 liters/cum (20 to 35 lbs/cuyd) and the mixtures responded better to vibration and finishing. Dubbed the “haystack”, that particle distribution was found to correlate with the combined aggregate following the gradings from ASTM C33-23 and DCC Issue 1. A comparison of grading is shown on Figure 4.

The findings based upon this technology are leading to changes in industry and state agency standards. ASTM C33 was modified in 1993. The “Scope” provides that when a coarse aggregate is specified by size number, the aggregate must meet the ASTM C33 quality requirements and have the nominal maximum aggregate size for that classification. A concrete producer does not have to follow the grading in the table. The gradings in the table may be used by purchaser of aggregates in a purchase agreement. Paragraph 4 includes other limitations. The “Scope” also includes provisions for the addition of *“blending sizes when directed or approved”* to produce a better combined grading. It is expected the approval caveat will be removed in the near future. The committee also has on its agenda the introduction of a coarse sand alternative to he similar to that used before 1938.

ACI 301-96 (17) provides an alternate to specifying aggregate grading. Limits are provided for not more than 18% nor less than 8% of the combined aggregate to be retained on an individual sieve except the coarsest and the finest. There is a caveat for slivered particles that cause interference to mix mobility. The authors feel other procedures are more effective.

Over the past decade, the authors have tracked hundreds of mixtures and resolved problems found during pumping, placing, finishing, cracking, and curling. Based upon these data and field observations, the Coarseness Factor Chart was modified to include “zones” shown on Figure 2 to predict performance. Following is the interpretation of the zones and sub-zones:

Zone I - High potential for segregation due to poor combined aggregate grading with a deficiency in intermediate (passing the 3/8” and nominally retained on the No. 8 sieve) particles.

Zone II - The optimum zone for mixtures with nominal maximum aggregate size from 1-1/2” Through 3/4’. Sub-zones are:

0 - The optimum for a rounded gravel or cubically crushed stone with a natural coarse sand. It requires excellent control of aggregate grading and prevention of segregation in the stockpile or in the bin. It segregation occurs, a batch may fall into Zone V and not be plastic.
1 - Similar to “0” but it is more flexible.
2 - Excellent for slip formed construction with good particle shape aggregates and

control.

3 - Good slip-form concrete. Highly workable for gravel or cubically crushed stone mixtures and has been pumped for bridge decks. May be used for formed flat work.

4 - All-around mixture for many purposes including placement in reinforced vertical construction

5 - A zone where problem aggregates or equipment problems make it necessary to have more than the desirable amount of fine mortar in a mixture.

Zone III - An extension of Zone II for 1/2" and finer aggregate mixtures.

Zone IV- Excessive fines in the mixture. Commonly referred to as the 'Courthouse' due to the potential problems. High potential for segregation during consolidation and finishing.

Zone V - Too much coarse aggregate - non plastic.

Zone I concrete can be recognized during placement. When placed by chute or belt, the coarse aggregate is thrown forward and the mortar recedes below the conveyor. When that occurs, the integrity of the concrete is lost. Specifications for sampling and testing prevent recognition of this problem, as the concrete must be remixed before casting samples. In practical terms, the in-place concrete will be two or more mixtures that are derivatives of the original mixture. The coarse portion with inadequate fine mortar and over-mortared portions can each account for spotty performance of concrete. The problems may appear immediately or not appear for many years but they will occur and increase maintenance cost.

The segregation can cause two problems at slip—formed pavement edges. The portion of the concrete with the high incidence of coarse materials can be finished at the edge but slough due to a deficiency in binder. When the highly mortared portion of the mix is formed at an edge, it can be affected by incidental vibration and slumps due to its lack of stability. In the main body of the pavement, the low fines can be permeable and abrade rapidly. High fine mortar in the main body can segregate to the top during vibration and contribute to spalling at saw cuts and early or long-term scaling.

Zone IV concrete contributes to practically all undesirable characteristics of hardened concrete including: variable strength, shrinkage, cracks, edge slump, curl, scaling, spalling, cracks over vibrator trails, rapid surface wear, and highway roar in later years. A related factor is dowel bars may drift after insertion.

A common problem for Zone IV mixes is they segregate severely during placement and consolidation and finishing. The mortar, with a high concentration of water, air, and chemicals, rises to the top. Finishers move it around with a bull-float or highway straight edge to try to overcome variations in flatness caused by this type mix. This can be compared to applying icing to a cake - the cake and icing are not the same materials. Since the compacted concrete and weakened mortar are not the same, the top of the concrete is stratified and tends to spall at saw joints and scale with time.

Cramer, et at (18) reported results of a Wisconsin DOT demonstration proect "to investigate Shilstone." Of special interest was the vibration study comparing their traditional mix and the better graded (optimized) mix. Concrete was placed in PVC cylinders and vibrated 20 seconds, 1 minute, and 3 minutes. Four layers were wet-sieved to determine the effect of vibration on aggregate segregation. The three-minute vibration caused major segregation in the traditional mix ("W" Figure 2). The 19mm (3/4-inch) made up approximately 37% of the combined aggregate in the bottom quarter. In the top quarter, that size accounted for only 9% of the total aggregate. The bottom portion included about 10% of the material retained on the No. 50 sieve while it accounted for 24% of the aggregate on the top. Very little segregation occurred with the optimized mixture (“X’ Figure 2).

The U. S. Air Force, in an effort to resolve problems affecting high-performance aircraft, demonstrated the validity of the forgoing positions. Numerous airfield pavements constructed since 1987 developed early distress. Problem pavements were constructed by different contractors, designed and managed by different construction agents, and were subject to different types of aircraft loading. The distress is the same regardless of geographical location.

Failures included sliver spalling along joint reservoirs extending to the depth of the reservoir and appearing randomly along both transverse and longitudinal joints. The early distress appeared after the first change of season after the construction, usually a freeze-thaw, and continued to get worse with time and traffic. Distress also included some raveling of the surface near joints and joint intersections.

Two venues for problem resolution were pursued. Those pavements with early distress were examined in detail by the extraction of cores and subsequent petrographic study. The conclusion of the study was not specific as to the cause, nor the solution, of the observed distress. Poor mixture proportioning, poor workmanship, and a lack of knowledge of the construction techniques for airfield pavements were offered as general observations for each of the projects studied (19). The hypothesis offered was that poor mixture designs and variable concrete were directly responsible for workmen resorting to poor construction practices m attempts to produce visually acceptable pavement placements.

A parallel evaluation involved the construction industry. Contractor members of the American Concrete Pavement Association (ACPA) visited sites where early distress was in an advanced stage of development. The general observation was that the pavement appeared to be over-finished and there was segregation of the aggregates and paste at the pavement surface. The spalled areas were primarily of paste with no large size aggregate present.

USAF engaged the Civil Engineering Research Foundation (CERF) as facilitator to bring together engineers, suppliers, contractors, and concrete consultants to cooperatively develop a solution to the Air Force needs. It was suggested that the original conclusion of poor mix designs was correct but the major problem was the variability in grading of the aggregates.

The USAF pursued the conclusions by looking at construction records and performance history for both good and poor pavements constructed since 1987. In all cases the aggregate gradings complied with the specified ASTM C33 criteria but the combined aggregate grading was highly variable. The percent of the combined aggregate retained on each sieve was plotted. In most cases it was found to be gapped and the broader the gap, the closer the relationship with the problems. The particularly troublesome projects involved coarse aggregate to meet ASTM C33, size 57 and a relatively fine concrete sand as discussed herein.

The Coarseness Factor Chart with the zones was included in the study program. Construction was monitored with particular emphasis on aggregate grading. Contractors with mixes plotting in Zone I had continuing problems. Some used mixes that bridged between Zones I and II. They had good days and bad days dependent upon which zone. The contractors continually in Zone II had few problems and their projects are still performing to expectations.

LaFrenz (20) reported the findings from one of the several projects that demonstrated the correlation between the Coarseness Factor Chart (Figure *5)* and the work. Samples of aggregates were collected from conveyor feed belts. The weighted proportions, which were used for the mixture, were used to determine the Workability and Coarseness Factors. The mixture design is identified by “D.’ Those paving lanes plotted as “X” were successfully placed and to date have not shown evidence of early distress. Those paving lanes with materials which plotted as “S’ have spalled over the changes in season from fall through winter. The F" reflects over finishing probably due to the excess mortar that rose to the surface. A rocky mixture is identified by an "R".

The evidence is that controlling combined aggregate grading for concrete mixtures will improve both the constructability and, subsequently, improve the performance of concrete pavements. The ACI 211 and percent of aggregate methods for concrete mixture proportioning do not provide a means to consider combined aggregate as an entity. These methods can result in poorly or gap graded aggregate concrete when used with aggregate selection using ASTM C-33 grading limits. Because of this evidence, the USAF has implemented a construction specification which requires gradation control for concrete to be used for airfield pavements. In addition, a concrete mixture proportioning handbook was developed and issued.

The 21st Century Paradigm:

The 21st century paradigm will be a combination of early technology and experience with current materials, methods, and performance objectives coupled with computer science. The mystery of concrete mixtures will be removed. It will be recognized that the portion of the earth's crust used as concrete aggregate varies within quantifiable limits. The paste that binds the aggregates together also varies within quantifiable limits. Where similar materials aggregates and paste occur, a mixture that performs well in one part of the world will perform equally well in any other part of the world. Thus, worldwide standard mixes will be defined as suggested by the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) for the last 15 years.

Abrams (5) addressed the need to recognize two terms related to mixtures. He wrote, *The term "Design" is used in the title of this article as distinguished from "proportioning" since it is the intention to imply that each element of the problem is approached with a deliberate purpose in view which is guided by a rational method, if accomplishment. The design of concrete mixtures, with a view to producing a given result in the most economic manner. involves many complications which have heretofore defied analysis."*

ACI Committee 211, "Proportioning Concrete" recommended clarification of terminology for mixtures. Only "mixture proportions" is an accepted term within ACI Terminology. The Committee defined a new term for "mixture design" as, *"a quantified description of a grout, mortar, or concrete mixture developed, evaluated, and tested to meet the specified requirements for strength. construction, durability, and/or other performance goals".* The mixture proportions are the contractor's solution to the design.

Once a mixture is developed and tested to assure construction and durability goals can be met, that design can be maintained as long as the materials described in the referenced design are used. Locally, during construction, tests to verify performance-based requirements are met can be made and the mixture design adjusted, as necessary, to keep up with materials changes that occur especially in the paste. It will be up to the contractor to use his materials and methods skills to replicate that design at the lowest possible cost. A mixture design may he little more than the following:

Materials: Portland cement, pozzolanic materials, admixtures, air entraining agents, and aggregates with a nominal maximum aggregate size of l-l/2inch shall meet the quality requirements of the DOT Manual.

Mixture: Water-cementitious materials ratio shall be 0.45 or less, air content shall be 5.0 ± 1.5%, combined aggregate Coarseness Factor shall by 68% (± 5 points parallel to the Trend Bar), and the Workability adjusted for cetnentitious materials shall be 34 (± 4 points)

Quality Control: During construction, test materials in use and make adjustments to replicate the mixture design.

With the mixture design terminology accepted, the authors see the following as the 21st century concrete paradigm:

- Contract documents will be performance-based and cite the mixture design appropriate for the region where the work will be done. The quality of the concrete will be specified rather than just the ingredients.
- A concrete technology computer separate from the batch computer will manage the mixture design and provide technical support for the production of concrete meeting the requirements of ANSI/ASQC Q9000. The mix management portion will be supported by databases for aggregates, cementitious materials, pozzolanic materials, and, if suitable measurements can be determined, admixtures. It will also have a statistical analysis segment to correlate and analyze all production data and for later study.
- Lasers or other methods will be used to verify the grading shape, and texture of aggregates as they fall into the bins and forward that data to the technical computer. Other materials data will be provided by suppliers by modem to provide real-time control of production.
- The technical computer will be the center for QA\QC data. It will correlate production data and test results. Using statistical methods, a compression strength test may be correlated with a projected flexural strength. Or, it may be determined that the primary factors that affected a change in compressive strength was a change in the loss on ignition of the cement and an increase in minus No. 50 sieve particles in the aggregate. Any of hundreds of reports can be produced at the user's option. At the conclusion of the project, disks with all records will be supplied the agency for future use.
- A professional concrete engineer will emerge and be recognized as a major party to high-performance concrete. He will come from the ranks of industrial engineers as concrete construction will be recognized as a manufacturing process requiring manufacturing skills. Such a program is underway for basic concrete technology to support the ready-mixed concrete industry. The first class of four-year degree concrete technology engineers will graduate from the University of Middle Tennessee in the year 2000.

These are not pipe-dreams. Everything is proven and can he in use by the year 2000. The major problem will be man's reluctance to give up a paradigm that has contributed to the National Materials Council report titled **"Concrete Durability - A Multi-Billion Dollar Opportunity"** to the U.S. Congress. That change must come to assure a sustainable infrastructure.

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Figure 1 – Cores: 1986 casting on left and 1929 casting on right

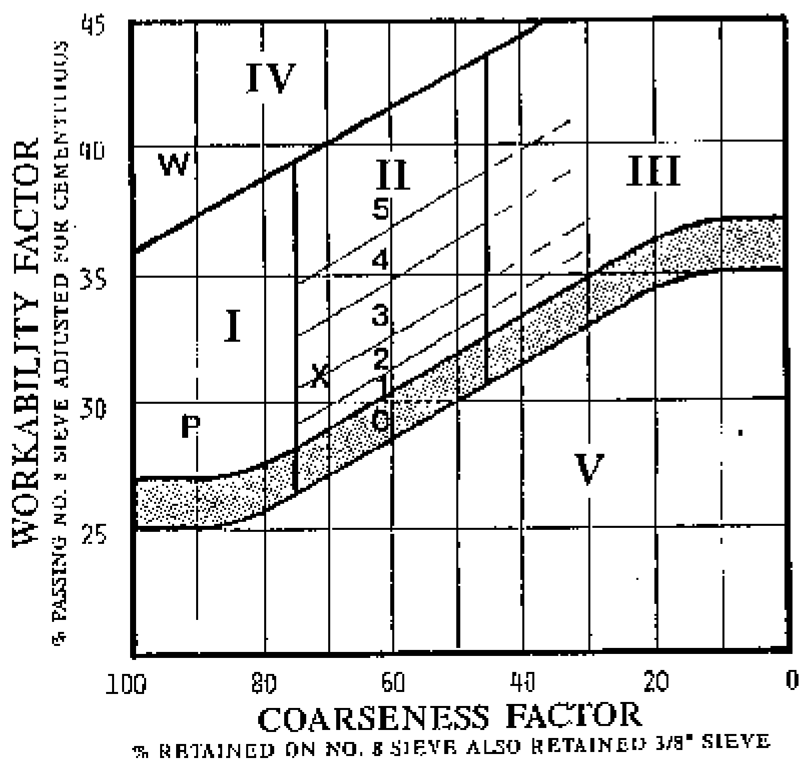

Figure 2 - Coarseness Factor Chart as modified 1996

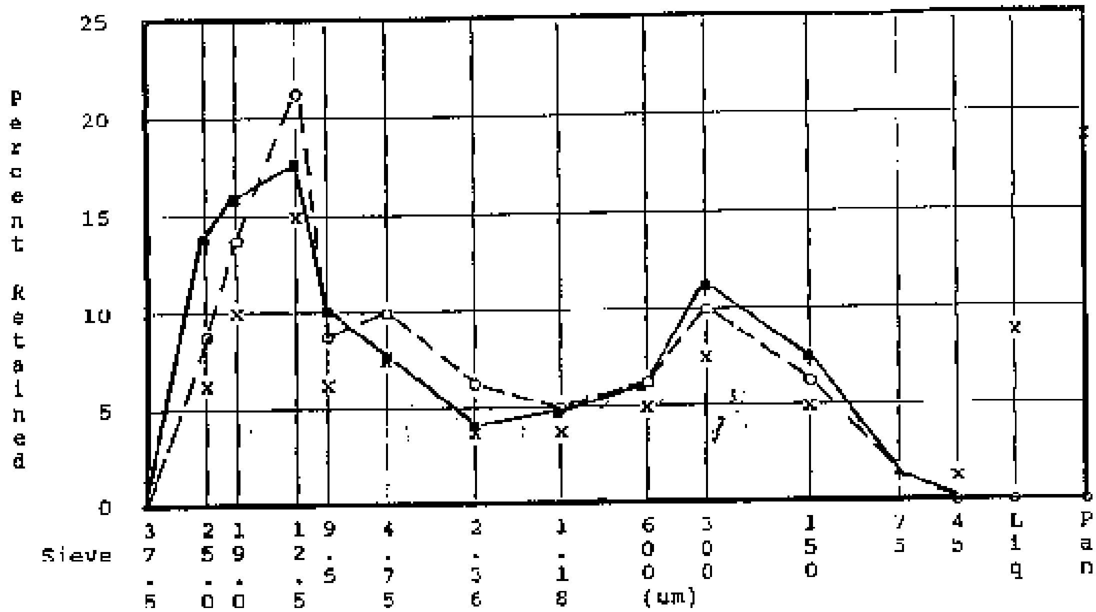

Figure 3 - Gap-graded particle distribution from widely separated projects

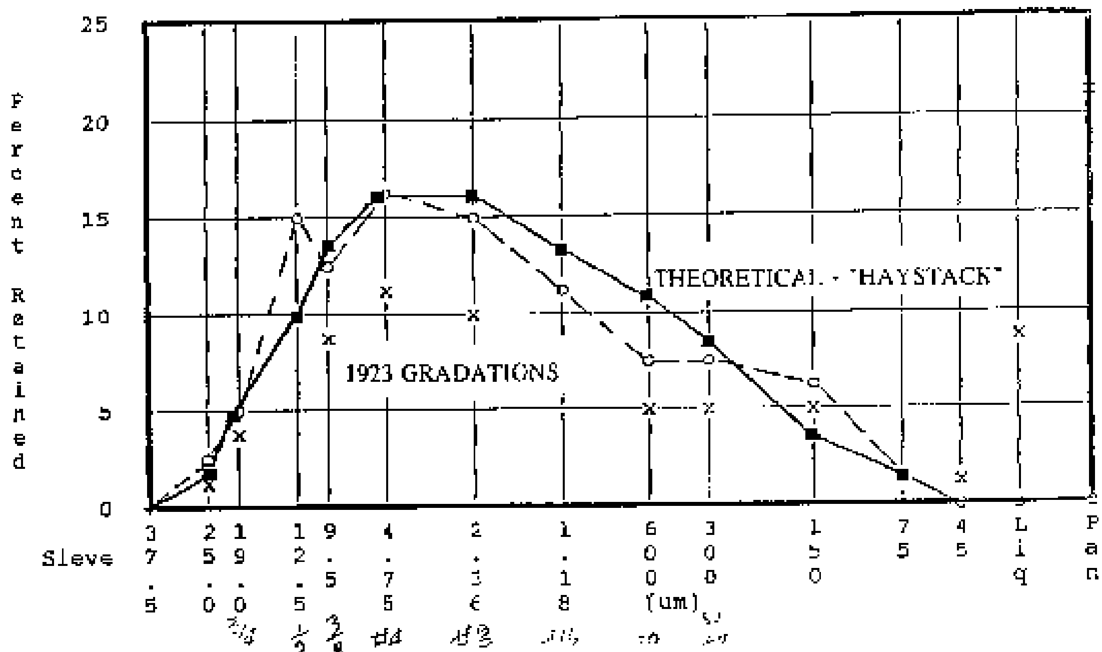

Figure 4 - Aggregate particle distribution - "Haystack" vs 1923 standards

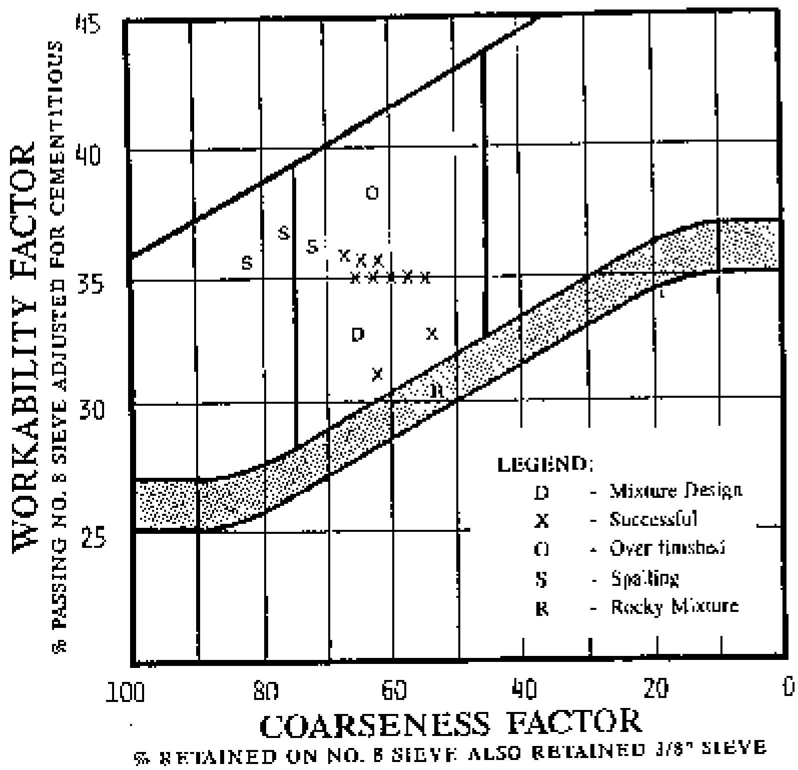

Figure 5 - U. S. Air Force experience with Coarseness Factor Chart