

EVALUATION OF STRENGTH TESTS
AND ACCEPTANCE OF CONCRETE PAVEMENTS

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ABSTRACT

One of the most troublesome phases of a concrete pavement construction project can be the determination of whether the strength of the concrete meets the project specifications. This determination can be complicated by the fact that the flexural strength test is often the test specified for acceptance and there is often little or no understanding of the procedures and precision of the flexural strength test. The quick placement of large volumes of concrete for pavement construction projects means that a million dollars or more worth of concrete can be "on the ground" before the first acceptance test is ever performed. If questions arise regarding the validity of the acceptance tests, then a good understanding of the variations inherent in the flexural strength test are necessary for a proper evaluation of the acceptability of the concrete.

The results of analyses to determine the statistical parameters for flexural strength test results for more than one million cubic yards of concrete pavement constructed at the Atlanta International Airport are presented in this paper. Parameters for within-test statistical variations are presented so that the quality of the testing agency personnel can be evaluated. Parameters for the between-test statistical variations are presented so that the quality of production by the contractor can be evaluated. The results of the analyses indicate that the within-test variations can approach the between-test variations and this greatly contributes to the confusion and misunderstandings. The analyses also show that two flexural strength test results from the same batch of concrete can be expected to vary by as much as 100 psi and not be considered suspect 95 percent of the time. The difference between the average flexural

strengths of each of two batches of the same concrete mix in the laboratory can differ by as much as 75 psi and not be considered suspect 95 percent of the time.

Procedures for adjusting the actual flexural strength test results upward based on additional thickness over the design thickness or downward based on deficient thickness from the design thickness are given. The use of compressive or split tensile strength test results in lieu of flexural strength test results for the acceptance testing for concrete pavement construction projects are also presented.

INTRODUCTION

The thickness design of concrete pavements generally requires the following basic parameters:

1. The number and magnitude of design load applications.
2. The subgrade support value.
3. The concrete flexural strength.
4. The thickness of the concrete pavement.

Given any three of the above parameters, the designer then can determine the fourth. The normal design process involves using the subgrade support value, the number and magnitude of load applications and the specified concrete flexural strength to determine the concrete pavement thickness. Contract documents are then prepared which require the contractor to provide a concrete pavement with the specified thickness and flexural strength. During the construction phase, the designer normally requires that the physical properties of the plastic concrete such as slump and air content be within specified ranges. The pavement is finally accepted and paid for

on the basis of flexural strength test results (in third point loading ASTM C 78) typically at 28 days or 90 days.

Since concrete gains strength with time and concrete pavements are generally in place for some significant period of time prior to being subjected to traffic, the actual design thickness may be based on the probable flexural strength at 90 days. The flexural strength at 90 days is usually assumed to be 10 percent greater than the 28 day flexural strength [1,2]. However, this is an average value and individual mixes may vary from 0 to 20 percent depending on the type of cement and other characteristics of the materials. The 28 day flexural strength is still used as the acceptance age because no one wants to wait more than 28 days to determine acceptance. This is particularly true when one considers that with today's equipment, a contractor can produce and place more than 1 to 2 million dollars worth of concrete before the first acceptance strength test is ever performed. Thus it is clear that it is to everyone's benefit (the owner, the designer, the contractor, and the supplier) that the concrete produced for the project be adequately designed and controlled and that the acceptance criteria be realistic. It is also extremely important that the testing for acceptance be performed properly and in accordance with the contract specifications.

The flexural strength test results are subject to many factors during fabrication, curing and testing which can cause relatively large variations. These variations are often misunderstood, confused with variations for compression strength test results which are significantly different from those for flexural strength test results and misapplied. The variations in flexural strength tests also complicate the evaluation and acceptance. This lack of understanding and complexity often results in many tens of thousands of dollars of removal and replacement costs and penalties. It can also escalate the cost of later concrete pavement construction projects as contractors and suppliers try to cover their previous losses.

When the flexural strength test results fail to measure up to the specified values, disputes which can be very difficult to resolve often occur. The testing agency is blamed for poor testing and the contractor is blamed for producing a poor product. In the case of buildings, the American Concrete Institute has published clear criteria for evaluation of strength test results and for determining whether the testing agency and/or the contractor

may be at fault [3]. Although the procedures apply to flexural strength test results, no evaluation criteria are given for the flexural strength test results. Thus, there is a significant need for the development and publicizing of parameters for flexural strength tests.

The results of analyses to determine the statistical parameters for flexural strength test results for more than one million cubic yards of concrete pavement constructed at the Atlanta International Airport are presented in this paper. Parameters for within-test statistical variations are presented so that the quality of the testing agency personnel can be evaluated. Parameters for the between-test statistical variations are presented so that the quality of production by the contractor can be evaluated. Very good quality control by the contractor can result in overall coefficients of variation in the range of 5% which are approximately one half the variations for compressive strength results. The results of the analyses indicate that the within-test variations can approach the between-test variations and this greatly contributes to the confusion and misunderstandings. The analyses also show that two flexural strength test results from the same batch of concrete can be expected to vary by as much as 100 psi and not be considered suspect 95 percent of the time. The difference between the average flexural strengths of each of two batches of the same concrete mix in the laboratory can differ by as much as 75 psi and not be considered suspect 95 percent of the time. Yet an analysis of the Federal Aviation Administration concrete pavement design charts shows that a 1 or 2 percent change in flexural strength theoretically can change the allowable traffic by as much as 10 to 20 percent [2].

An analysis of the Federal Aviation Administration concrete pavement design charts shows that the load carrying capability of a concrete pavement is a power function of the ratio of the actual thickness to the design thickness. Procedures for adjusting the actual flexural strength test results upward based on additional thickness over the design thickness or downward based on deficient thickness from the design thickness are given. The use of compressive or split tensile strength test results in lieu of flexural strength test results for the acceptance testing for concrete pavement construction projects are also presented.

LABORATORY MIXES

One of the first steps in the preparations for initiating concrete pavement construction is to select a mix design for the project. This is usually accomplished by the contractor delivering samples of the proposed materials to an independent laboratory where the proposed proportions are mixed, physical characteristics of the mix such as slump, air content and unit weight are measured and specimens for flexural strength testing at the ages of 3, 7, 14 and 28 days are prepared. In some cases later ages may also be used either for informational purposes or for specifications which require later ages. Generally laboratory mixer size limits the number of test beams to approximately nine. The laboratory testing may be set up to confirm or verify a particular mix that the contractor has been using or it may be set up to evaluate a wide range of combinations of materials. As many as 40 to 50 mixes may be prepared and evaluated for very large projects.

One of the things so often overlooked by owners, designers, engineers, contractors and suppliers in the laboratory concrete mix evaluation phase is the laboratory variability. Although the laboratory conditions are considered the most well controlled of any place in the construction industry, variations do occur and they must be properly understood and applied to evaluations if problems are to be avoided during the construction phase. The American Concrete Institute (ACI) has published detailed procedures and criteria for the evaluation of concrete compressive strength test results. Although the procedures apply to flexural strength test results, no evaluation criteria are presented for flexural strength test results. The application of the compressive strength criteria to flexural strength can result in erroneous and unobtainable requirements.

In the laboratory, the two variations of the greatest concern are the within-test standard deviation and the between-test standard deviation. The within-test standard deviation indicates the amount of variation among flexural strength tests from the same batch of concrete and is an indicator of the quality of the procedures by the laboratory personnel. The between-test standard deviation indicates the amount of variation between different batches of the same concrete materials.

Within-Test Standard Deviation: Published literature for laboratory concrete flexural strength tests for almost 200 mixes related to the expansion of the Atlanta International Airport in the

1970's and numerous mixes for research by Walker and Bloem in the 1950's indicated average within-test standard deviations of 33.5 and 39.0 psi, respectively [4,5]. These values correspond to coefficients of variation in the range of 4 to 8 percent. This is significantly more than the 2 to 4 percent range which is considered excellent to good for compressive strength [3]. ACI 214 indicates that compressive strength test results have within-test standard deviations which vary with strength level and coefficients of variation which are considered to be independent of strength, therefore, the coefficient of variation is the criteria used for compressive strength within-test variation. The published data for the Atlanta Airport and the other projects indicate that the within-test standard deviation for flexural strength is independent of strength as illustrated in Figures 1 and 2. Therefore, the within-test standard deviation is more appropriate for the evaluation of flexural strength tests than is the coefficient of variation. Based on current ASTM procedures for the precision limit calculations, two beams from the same batch of concrete could differ by up to 100 psi approximately 95 percent of the time and still be considered acceptable.

Between-test or Between-batch Standard Deviation: The published literature in References 4 and 5 for laboratory concrete flexural strength test results where multiple batches of each mix type were prepared indicated average between-test or between-batch standard deviations of 26.9 and 28.0 psi, respectively. Based on current ASTM procedures for precision limit calculations, two batches of the same mix could differ by 75 psi up to approximately 95 percent of the time and still be considered acceptable. This can have very important ramifications in the evaluation of single or multiple batches of the same mix in the laboratory, particularly when one considers that the common "overdesign" criteria for flexural strength concrete in the laboratory is in the range of 60 to 80 psi. As for the within-test standard deviations, the between-test standard deviations were generally independent of the strength level as illustrated in Figures 3 and 4.

Typical practice for laboratory concrete mix flexural strength testing involves making several test beams (usually six to nine) and testing them (usually two to four) at ages of 3, 7, 14, and/or 28 days. This brings up the question of what would occur if all of the beams in a batch were tested at the age of 28 days and how would the expected variation affect the test results for a given batch when only three or four beams are tested at a given age.

In other words, what would the range of test results be if the highest three or the lowest three test beams were inadvertently selected for testing at 28 days.

For the Atlanta Airport mix designs, two batches of concrete were prepared for each of two different concrete mixes and all beams were tested at 28 days. The significant aspect of the data obtained was the relatively large difference between the average flexural strengths of the highest three and the lowest three beams within a given batch. The differences between the average flexural strength of the highest three beams and the lowest three beams within a batch ranged from 42 to 58 psi despite the fact that all of the batches had within-test standard deviations which were at or below the overall average for the Atlanta Airport mixes [4]. While the odds of selecting the highest three or the lowest three beams are relatively low, it can and does happen and can greatly affect the evaluation of a single batch or a series of mixes, particularly if only one batch is prepared for each mix.

FIELD TESTING AND QUALITY CONTROL

General: The concrete for the Atlanta International Airport expansion projects encompassed more than one million cubic yards with individual projects ranging from 10,000 cubic yards to 450,000 cubic yards. All concrete was produced in on-site central mix plants, hauled to the paver site in non-agitating dump trucks and placed, consolidated and finished by slipform paving techniques. Concrete production ranged up to 3000 cubic yards per day with typical averages of 1000 to 1500 cubic yards per day.

The concrete mixes contained Number 4 and Number 67 crushed granitic gneisses as specified in AASHTO M80 [6]. The fine aggregates were manufactured from granitic gneiss or were natural sands complying with AASHTO M6 [6]. The mixes all had water reducer and/or set retarders and contained 6.0 to 6.5 bags of Type I cement per cubic yard. The slump was specified at one inch plus or minus one-half inch with an entrained air content of 4 to 6 percent by the pressure method.

Control Procedures: In order to control the large amounts of concrete involved on the paving projects, a very thorough testing and inspection program was performed. The inspection program was executed by representatives of the designer and an independent construction inspection consulting firm retained by the

owner through the designer. The batch plants were checked numerous times each day by engineers and technicians to document batching procedures and to determine moisture contents of the aggregates so that moisture corrections in the batching process could be verified and changed where necessary. Samples of the aggregates were obtained on a daily basis to determine if the aggregates complied with the specified gradations.

The concrete used for paving was sampled at the point of lay-down for slump and air content, and flexural beams were prepared for testing. The making and curing of the beams was one of the most significant quality control aspects of the Atlanta Airport projects. On the first contract (Contract 31) in 1974, the beams were made near the pavement and covered with plastic. A wooden frame, draped with wet burlap was placed over the beams to shade them from the sun during the first 24 hours after sampling. On subsequent projects, the concrete was sampled at the point of lay-down and returned to a central location where the beams were prepared in small portable buildings (10 feet by 10 feet), covered with plastic, and cured during the first 16 to 24 hours. The buildings were heated in winter and air conditioned in summer to maintain the air temperature around the beams between 60° F and 80° F during the first 16 to 24 hours as required in ASTM.

Upon completion of curing for the first 16 to 24 hours, the beams were returned to portable or semiportable laboratory facilities on-site. The beams were placed in saturated limewater curing tanks, which were temperature controlled to maintain a water temperature of 73.4° F $\pm$ 3° F, as required in ASTM, until they were ready for testing.

Within-test Standard Deviation: The within-test standard deviation in the field test results is an indicator of the quality of the procedures by the testing personnel. The analysis of the data for the Atlanta Airport projects indicated average within-test standard deviations for projects ranging from 31.3 psi to 41.3 psi with an overall weighted average of 34.7 psi. This value is virtually identical to the average standard deviation of 33.5 psi for the Atlanta International Airport laboratory mixes. The limited data available for 3 day tests indicated average values ranging from 24.2 psi to 33.4 psi with an overall average of 28.6 psi. Figure 5 presents a plot of average within-test standard deviation versus flexural strength for the various Atlanta Airport projects. Although the number of data points is limited, it would appear that the average within-test standard

deviation is only slightly dependent on flexural strength. Thus, the within-test standard deviation is the appropriate parameter for evaluation of within-test variation in field testing. This is also different from ACI 214 which utilizes coefficient of variation to evaluate within-test variation in field tests for compressive strength. No data for within-test standard deviation for other projects was readily available for analysis.

Between-test or Between-batch Standard Deviation: The between-test or between-batch standard deviation values (indicators of the quality of the production and control procedures by the contractor and supplier) for flexural strength tests at 7 days for the Atlanta Airport projects ranged from 25.2 to 47.4 psi with an overall weighted average of 42.1 psi. The standard deviation values for the 28 day test results ranged from 25.5 to 52.7 psi with an overall weighted average of 35.1 psi [7]. It is important to note that this value (although based on two tests per batch) is almost identical to the within-test standard deviation both in the field and in the laboratory. The standard deviations ranged from 18 to 120 psi and 26 to 122 psi at 7 and 28 days, respectively, for published data for other projects [8]. The overall weighted average standard deviations for the other projects were 67.6 and 65.0 psi at 7 and 28 days, respectively [7]. Figures 6 and 7 present the frequency histograms for the standard deviation at the two ages for both the Atlanta data and the other data. Figure 8 also indicates that the between-test or overall standard deviation is independent of flexural strength and therefore is the appropriate parameter for evaluation.

It is not clear from the published data for the other projects what specific quality control procedures were used. However, it is assumed that the quality control procedures for the Atlanta Airport projects were at a higher level than for the other published projects, particularly for the batch plant inspections and the curing of the beams during the first 24 hours.

The data for the Atlanta Airport projects indicate that the high level of batch plant monitoring reduced the material variability for the Atlanta Airport projects with the exception of air content as compared to the published data [7]. The most significant decreases were achieved in the variability of the flexural strength data, the primary criteria for evaluation of the acceptability of the concrete. The effect of good initial curing would appear to be that of raising the average strength over

that for poor initial curing. Contract 31 at the Atlanta Airport, the first major contract in the expansion program, had approximately the same variability in flexural strength as the projects which had excellent initial curing. However, the flexural strengths were significantly lower than for the other Atlanta Airport projects. Higher temperatures in concrete during the initial curing have been shown to decrease the long-term strength of concrete [9].

EVALUATION OF FLEXURAL TEST RESULTS

As mentioned previously, when the flexural strength test results fail to measure up to the specified values, disputes erupt as to who is at fault and economic penalties and/or removal of concrete is threatened. The testing agency is blamed for poor making, curing, handling and testing of the beams. The contractor and supplier are blamed for producing a poor quality concrete. A big issue then arises as to how to evaluate the flexural strength of the concrete in-place to confirm whether or not it complies with the specifications or the intent of the design.

A first step in this process is to compare the within-test standard deviations, if two or more beams were tested per batch, for the project in question with typical published values. This will allow an evaluation to be made as to the general quality of the procedures by the testing personnel and the validity of their test results. The next step is to compare the between-test or between-batch standard deviation for the flexural strength test results in order to evaluate the general quality of the concrete produced by the contractor or supplier. The following values have been proposed by this author for these comparisons and evaluations of field flexural strength data:

WITHIN-TEST STANDARD DEVIATION (TESTING AGENCY)	OVERALL STANDARD DEVIATION (CONTRACTOR)	LEVEL OF QUALITY CONTROL
< 40 PSI	< 40 PSI	GOOD TO EXCELLENT
40 - 65 PSI	40 - 65 PSI	FAIR TO GOOD
> 65 PSI	> 65 PSI	POOR TO FAIR

Once the general quality of the testing

agency procedures and the contractor or supplier procedures have been determined, questionable flexural strengths can be further analyzed based on the actual thickness of the in-place pavement. If the flexural strength is low, then the FAA design charts can be consulted to determine the necessary thickness for the lower flexural strength. If the contractor has been so fortunate as to construct the pavement slightly thicker than the design requirements, then the lower flexural strength can be offset. A simplifying formula for adjusting the actual flexural strength based on the actual thickness of the in-place pavement is as follows:

$$FS_{adj} = FS_{act} * (T_{act} / T_{req})^P$$

FS_{act} = Actual Flexural Strength (psi)
 T_{act} = Actual Pavement Thickness (inches)
 T_{req} = Design Pavement Thickness (inches)
 P = Constant ranging from 1 to 2

An analysis of the FAA design charts will generally show that the above relationship is reasonably valid within 1 to 2 inches of the design thickness. The designer can determine the proper value for P based on the design assumptions and add this adjustment procedure to the specifications. For the Atlanta International Airport Projects, a value of 2 was used for P. The value for P should be determined for each project based on the design parameters because it varies significantly depending on factors such as subgrade support and the general strength levels involved for the project. It should be noted that this is a two edged sword for the contractor because if the thickness of the concrete is also low then the contractor will be doubly penalized. Another way to evaluate the value of the in-place pavement is to determine the number of cycles of the design loads based on the actual field thickness and flexural strength relative to the number of cycles of the design load based on the design thickness and flexural strength.

If the above procedures do not resolve the issue of the acceptability of the concrete in-place, then it will be necessary to obtain and test samples of the in-place pavement. One of the accepted methods of evaluating questionable concrete compressive strength test results in building construction is to obtain and test cores in compression in accordance with ACI 318 [10]. Generally, 3 cores are obtained for each questionable area and the average compressive strength must be at least 85 percent of the design strength and no core may be less than 75 percent of the design strength. The strengths of the cores are allowed to be less than the

design strength for several reasons. The first is there is always a question of how the in-place strength of a structure compares to that of a test cylinder which is cured in a substantially different manner. The manner in which the core is obtained (location in the structure, direction of coring to direction of placement and method of conditioning) can greatly affect the results. Another reason is there is a significant amount of factor of safety which can allow strengths slightly lower than the design strength. Since pavements are designed with no factor of safety, the industry practice is to require strength tests of specimens obtained from the in-place pavement to equal or exceed the design strength. Also, samples are often times obtained at a significant time beyond 28 days and the issue of increased strength with time must be properly handled.

Since the acceptance of concrete in concrete pavements is based on flexural strength, the initial tendency is to cut beams from the in-place pavement and test them for flexural strength. However, these specimens are very difficult and expensive to obtain. The results are very sensitive to the care and conditioning of the specimens. Any surface microcracking as a result of the sawing process can significantly reduce the apparent or measured flexural strength. It has been the experience of this author that cutting and testing beams from the in-place pavement tends to result in flexural strengths which underestimate the in-place strength. Therefore, the recommended procedure is to obtain cores and test them in either compression or split tension. The split tensile test is the test recommended by the FAA because it more closely simulates the tensile failure than does a compression test [11]. Correlations between flexural strength and compression or split tensile test results have been published and can be useful for evaluation [12, 13]. However, it should be remembered that the published correlations are averages and the variation between published correlations and the correlation for a specific set of conditions on a specific project may vary significantly. Thus, it may be necessary to perform correlations for specific project conditions and materials.

SUMMARY

The following conclusions and recommendations are based on the data presented in this paper and the experience of the author:

1. The flexural strength within-test standard deviations as percentages of the flexural strength are two to four times greater than the compressive strength within-test standard deviations.
2. The relatively large within-test standard deviations for flexural strength tests are such that two beams from the same batch of concrete can differ by up to 100 psi approximately 95 percent of the time. Based on the Atlanta Airport data, the within-test standard deviation for field tests can approximate those for laboratory conditions if the field tests are performed properly and with care.
3. The relatively large within-test standard deviations for flexural strength tests dictate that at least 2 and preferably 3 or 4 beams be tested from each batch of concrete at the desired evaluation age.
4. The between-test or between-batch standard deviations for flexural strength tests in the laboratory as percentages of the flexural strength approach those for compressive strength tests. Published data for multiple batches of the same mix indicate that the average flexural strengths of each of two batches of the same mix can differ by up to 75 psi approximately 95 percent of the time. Because of this variation, it is recommended that two or more batches of each mix be prepared in the laboratory for the evaluation of mixes, particularly when the common "overdesign" strength for flexural strength concrete in the laboratory is 60 to 80 psi or approximately 10 to 12 percent.
5. The between-test or between-batch standard deviations for flexural strength tests in the field (based on two tests per batch) as percentages of the flexural strengths are approximately one half the typical values for compressive strengths. This allows the contractor to operate

with field strengths much closer to the design strength than is possible for compressive strength projects. This is the reason why flexural strength projects only need a laboratory mix strength which is approximately 10 to 12 percent greater than the design strength while compressive strength projects generally require laboratory mix strengths which are 20 to 25 percent greater than the design strength.

6. When flexural strength test results fail to measure up to the specified values, a three phase analysis procedure should be used to evaluate the in-place concrete before economic penalties are applied or concrete is specified to be removed:
 - a. The within-test (testing agency) and between-test (contractor or supplier) standard deviations should be compared to published values to assess the validity of the test results and the quality of the concrete. Values proposed by the author are included in this paper.
 - b. The in-place thickness of the concrete should be determined and utilized to adjust the actual flexural strength up or down depending on the thickness.
 - c. Cores of the in-place concrete pavement should be obtained and tested in compression or split tension. The flexural strength can then be estimated by utilizing correlations which are published or developed specifically for the project. The procedures of sawing beams from the pavement and testing them for flexural strength are not recommended due to high cost and the likelihood of questionable results.

7. The designer should specify flexural strengths which are routinely attainable with local available materials. The designer should specify very tight quality control procedures for both the testing agency and the contractor. The costs of the tight procedures are generally more than offset by reduced concrete costs and fewer problems or arguments about the quality of the in-place concrete.

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FIGURE 1.
WITHIN-TEST STANDARD DEVIATION
VS. FLEXURAL STRENGTH
LABORATORY - ATLANTA AIRPORT [4].

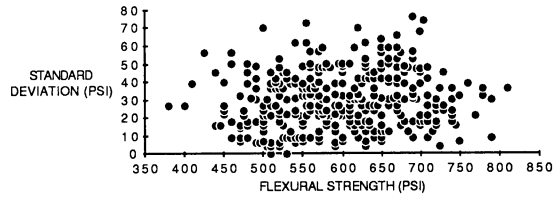


FIGURE 5.
WITHIN-TEST STANDARD DEVIATION
VS. FLEXURAL STRENGTH
FIELD TESTING - ATLANTA AIRPORT [7].

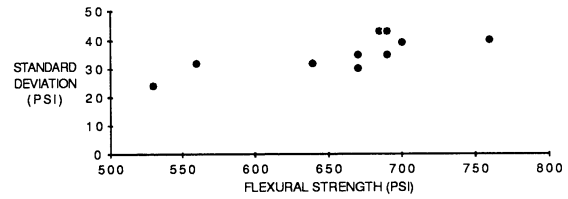


FIGURE 2.
WITHIN-TEST STANDARD DEVIATION
VS. FLEXURAL STRENGTH
LABORATORY - WALKER & BLOEM [5].

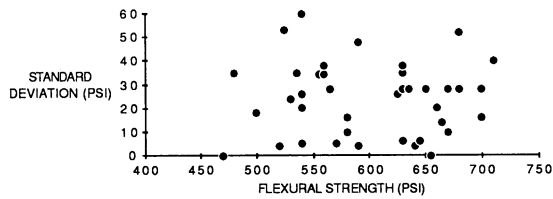


FIGURE 6.
FREQUENCY HISTOGRAM OVERALL STANDARD DEVIATION
AT 7 DAYS
ATLANTA AIRPORT & OTHER PROJECTS. [7].

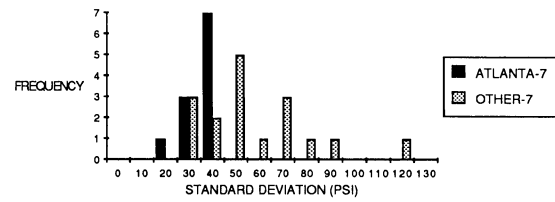


FIGURE 3.
BETWEEN-TEST STANDARD DEVIATION
VS. FLEXURAL STRENGTH
LABORATORY - ATLANTA AIRPORT [4].

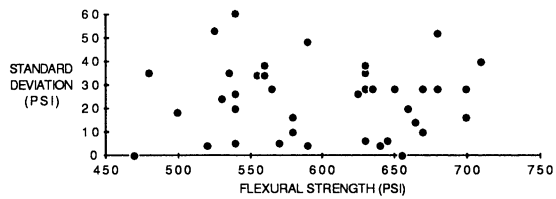


FIGURE 7.
FREQUENCY HISTOGRAM OVERALL STANDARD DEVIATION
AT 28 DAYS
ATLANTA AIRPORT & OTHER PROJECTS. [7].

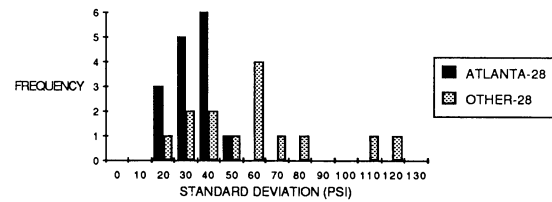


FIGURE 4.
BETWEEN-TEST STANDARD DEVIATION
VS. FLEXURAL STRENGTH
LABORATORY - WALKER & BLOEM [5].

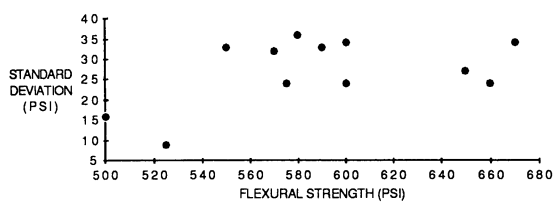


FIGURE 8.
BETWEEN-TEST STANDARD DEVIATION (CONTRACTOR)
VS. FLEXURAL STRENGTH
FIELD - ATLANTA AIRPORT

