PROPERTIES OF PLAIN AND REINFORCED LIMEROCK CONCRETE

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SYNOPSIS

The problem of securing aggregates satisfactory for construction purposes is often quite difficult in Florida since no deposits of hard igneous or metamorphic rocks occur and the sedimentary rocks are scarce and not as hard as some which occur in other states. Florida does possess large deposits of a soft limestone commonly called "limerock". Limerock has been used in the manufacture of lime, cement, concrete masonry block and for road bases and stabilization of soils. If limerock, with its large deposits and widespread distribution, should prove satisfactory for use in paving and structural concrete its use should do much to relieve the Florida aggregate shortage.

This paper reports test results obtained on approximately 1800 specimens in an attempt to determine in what way and to what extent the physical properties of limerock concrete differed from conventional concrete. Quantitative data are presented relative to bond, elasticity, thermal expansion, water requirements, compressive strength, and flexural strength of limerock concrete. Also included are the results of a five year performance survey made for an experimental limerock test road.

Geologically, Florida is a very young state. No deposits of hard igneous or metamorphic rocks occur. Even the sedimentary rocks are scarce and not as hard as some which occur in other states. At times it has been necessary to transport rock for construction purposes from Alabama, Georgia, Mississippi and Cuba. Florida does possess large deposits of a soft limestone commonly called "limerock". The available quantity of this soft limestone is limited only by the height of the water table and the thickness of the overburden. If limerock, with its large deposits and widespread distribution, should prove satisfactory for use in paving and structural concrete, its use should do much to relieve the aggregate shortage in Florida.

This study of limerock concrete was begun at the University of Florida in 1943 to establish fundamental facts to guide in the use of limerock in plain and reinforced concrete. Reports (*1, 2, 3, 4, 5*)[1] of the progress of this work have been published periodically. This paper reports additional test results obtained on approximately 1800 specimens in an attempt to determine in what way and to what extent the physical properties of limerock concrete differed from conventional concrete. Quantitative data are presented relative to bond, durability, shrinkage, thermal expansion, water requirements, compressive strength, tensile strength, and flexural strength of limerock mortar and concrete.

[1] Italized figures in parentheses refer to the list of references at the end of the paper.

LIMEROCK

Occurrence and Description—The entire State of Florida is underlain by a soft, friable, creamy-white, porous limestone commonly called "Ocala limerock". The limerock takes its name from Ocala, Florida, the site of the first lime pit in the State. According to Cook (6) this limestone is the result of sedimentation in an open, fairly shallow sea during the late Eocene Age. Apparently there was insufficient fine material at the time of deposition to fill completely the void space between the large shells which probably accounts for the porosity and softness of the stone. The limerock outcrops (6) in Florida are shown in Figure 1. At other locations the overburden varies from a thin layer of sand to approximately 1200 ft. at Miami. The thickness of the Ocala formation is reported to vary from 50 ft. to 690 ft. (6). Limerock is readily dissolved by ground water, so that an area in which it is near the surface is usually dotted with sinkholes. Commercial pits, or quarries, are located in Alachua, Levy and Marion Counties and there are potential developments in Washington, Holmes and Jackson Counties (7).

Limerock has been used in the manufacture of lime, cement, concrete and masonry block; however, the major portion has been used for road bases and stabilization of soils.

PHYSICAL PROPERTIES

Limerock usually contains 97 percent or more calcium carbonate. Impurities consist

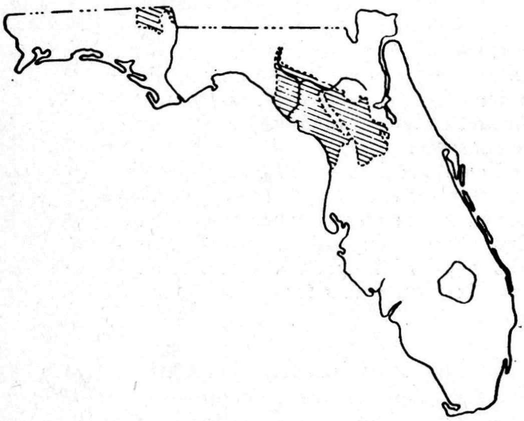

Figure 1. Ocala Limerock Outcrops in Florida

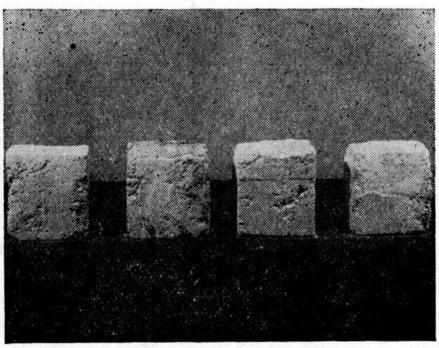

Figure 2. Hand Sawn Cubes

principally of flint and clay resulting from clogged sinkholes and solution channels. Organic impurities are not found when the overburden is removed properly. Limerock is extremely white when dry; however, it changes to a creamy yellow when saturated with water. No bedding planes are observed in a limerock quarry face, nor does it show a tendency to break along any plane.

Tests reported in this paper were conducted in accordance with ASTM standard procedures unless otherwise indicated. Limerock from a single source was used throughout the tests in order to minimize variables.

Large uncrushed samples of limerock were secured from which 6-in. cubes were hand-sawn as shown in Figure 2. This picture illustrates the porosity and softness of limerock. The cubes were tested in compression and failed at stresses varying between 300 and 700 lb.

TABLE 1

AVERAGE PHYSICAL PROPERTIES OF LIMEROCK AGGREGATE

Fine Aggregate	
Specific Gravity	
Bulk (oven dry)	2.04
Bulk (saturated surface-dry)	2.29
Apparent	2.69
Absorption, *percent*	11.4
Percentage of Crusher-run by wt.	78
Weight, *lb. per cu. ft.*	95
Gradation: *percent coarser*	
Sieve 4	0
8	12
16	28
30	44
50	63
100	82
Fineness Modulus	2.29
Coarse Aggregate	
Specific Gravity	
Bulk (oven dry)	1.88
Bulk (saturated surface-dry)	2.14
Apparent	2.57
Absorption, *percent*	14.1
Weight, *lb. per cu. ft.*	67
Los Angeles Wear, *percent*	65
Sodium Sulfate Loss, *percent*	18
Gradation: *percent coarser*	
Sieve Size $1\frac{1}{2}$	0
$\frac{3}{4}$	13
$\frac{3}{8}$	58
4	99
Fineness Modulus	6.71
Crusher-Run Aggregate	
Specific Gravity	
Bulk (oven dry)[a]	2.04
Bulk (saturated surface-dry)	2.26
Apparent[a]	2.66
Absorption, *percent*	12.0
Fineness Modulus[a]	3.25
Weight, *lb. per cu. ft.*	93.0

[a] Calculated.

per sq. in. with 445 lb. per sq. in. being an average for five tests.

Table 1 lists the physical properties of limerock received from a single pit over a period of nearly two years. From the average results it is seen that the samples of limerock used in this research were of uniform quality and that the fineness moduli were within the usually required limitations of plus or minus 0.2.

Referring to Table 1, it is seen that coarse limerock lost an average of 65 percent in weight when subjected to the Los Angeles Wear Test. This is a test for resistance to abrasion and the Florida State Road Department specifies a maximum loss of 35 percent for conventional aggregates. From Table 1 it is also seen that limerock coarse aggregate lost 18 percent in weight when tested in the sodium sulphate soundness test. Although this is greater than permitted by any state highway department, the test is a simulated freezing and thawing test and is of questionable importance in Florida.

Difficulty has been experienced in determining the percentage absorption of limerock. Values as high as 20 percent and as low as 10 percent have been reported. The absorption has been found to vary with the time the particles are in contact with the water, the method of saturation, that is whether saturated by capillarity or immersion, and also with the size of the particles. The test (C128-42) method for determining the absorption of fine aggregate established by ASTM was modified slightly for limerock. When using the slump cone, as outlined in C128-42, the point of saturated surface-dryness, that is the moisture content at which an aggregate particle would not change the amount of water available for hydrating the cement, was not distinct, therefore other methods were used. The point of saturated surface-dryness appears to have been reached when the aggregate changes color from a creamy yellow to white, when the aggregate just fails to leave a trail of water when wiped across a dry plane surface, when the material just ceases to cling together after being squeezed by hand and released, and when the aggregate surfaces just cease to glisten when exposed to rays of light.

Generally, an aggregate with an absorption of less than 3 percent is desirable for concrete because of the ease of maintaining the consistency of the concrete and reducing susceptibility to freezing, the latter being particularly important in the North. A theory, without supporting data, has been advanced that the water stored in porous aggregates can be drawn upon for prolonged curing of the cement paste (8).

Contrary to some previous work, limerock shows no tendency to take up moisture from the air even when an oven-dry sample is exposed to humidities approaching 100 percent.

When limerock is passed through a crusher with jaws opened 2 in., approximately 80 percent by volume of the resulting product is fine aggregate (minus No. 4 sieve) and 20 percent is coarse aggregate with the largest particles retained on the 1-in. sieve. Concrete made with a maximum size coarse aggregate of 1 in. usually has approximately 46 percent fine aggregate by volume in the case of angular coarse aggregate particles and 41 percent in the case of rounded particles. Particles of limerock are intermediate in shape so that 43 percent fine material might be more nearly ideal than the 80 percent found in crusher-run material. The additional fine particles materially increase the surface area to be covered by the cement paste without contributing a proportionate amount of volume.

In general, crusher-run limerock is finer than that permitted by the gradation specifications of the American Society for Testing Materials even when the fine and coarse aggregates are considered separately. The gradation of the fine limerock is such that approximately 18 percent passes the No. 100 sieve. This is 13 percent greater than the amount usually permitted.

LIMEROCK MORTAR

Procedure—The physical properties of limerock mortar using regular portland cement were determined for mixes containing one bag of cement combined with 300, 400, 500, 600 and 700 lb. of oven-dry limerock. The limerock was saturated before mixing and in order to secure the volume of mortar desired the preparation was essentially that outlined in ASTM method C87-46 except that the ratio of limerock to cement for a given mix was kept constant and the water-cement ratio was varied until a flow of 60 to 70 percent was obtained as measured by ASTM method C124-39. Each batch of mortar was made into specimens for determining the compressive strength, tensile strength, drying shrinkage, coefficient of expansion, and dynamic modulus of elasticity of the mortar mixes. The drying shrinkage was determined by comparing the length of 2- by 2- by 11⅜-in. prisms when cured one day with the length oven-dried after 28 days of curing. The thermal coefficient of expansion was measured from 2- by 2- by 11⅜-in. prisms over a temperature range of 70 to 212 deg. F. The modulus of elasticity was checked by the sonic method. Each mix is represented by at least two batches of mortar poured on different days. Specimens were cured in a moist room for·28 days at a temperature of 75 to 85 deg. F. and a relative humidity of 90 to 100 percent.

Results—Average results for limerock mortar are contained in Table 2. More detailed data for shrinkage, sonic modulus of elasticity and coefficient of expansion are shown in Figure 3.

The average values obtained for drying shrinkage as shown in Figure 3 appear to be normal. The sonic modulus of elasticity is slightly lower than usually expected. The coefficient of expansion, however, is only about one-third as great as is normally obtained for conventional concrete and for reinforcing steel. To further check the results, a series of tests were performed in which an equivalent absolute volume of quartz sand was substituted for the limerock. This sand is commonly used in Central Florida as a concrete sand and had a fineness modulus of 2.32. The volume of cement was kept constant and the water was varied to give a flow of 60 to 70 percent. After 28 days of curing, tests were run on the quartz sand mortar and the results compared to the limerock mortar. The average values obtained for all limerock mortar mixes when compared to the equivalent quartz sand mortar mixes reveals the following facts:

1. The average water-cement ratio for limerock mortar mixes was 10 percent less than for the quartz sand mortar mixes;
2. The average flow for the limerock mortar mixes was 3 percent greater than for the quartz sand mortar mixes;
3. The cement factor was 2 percent greater for the limerock mortar mixes than for the quartz sand mortar mixes;
4. The compressive strength was 23 percent greater for the limerock mixes than for the quartz sand mixes;
5. The tensile strength was 37 percent greater for the limerock mortar mixes than for the quartz sand mixes;
6. The drying shrinkage was 30 percent greater for the limerock mixes than for the quartz sand mixes;
7. The modulus of elasticity was 44 percent less for the limerock mixes than for the quartz sand mixes;
8. The coefficient of expansion was 68 percent less for the limerock mortar mixes than for the quartz sand mixes.

TABLE 2
AVERAGE TEST RESULTS OF LIMEROCK MORTAR

	Mix by wt.				
	94:300	94:400	94:500	94:600	94:700
Avg. W/C (Wt.)	.69	.91	1.00	1.12	1.26
Avg. Flow *percent*	60	70	65	65	65
Bags Cement per cu. yd. Mortar	7.0	5.5	4.6	3.9	3.5
Compressive Strength 2- by 4-in. cyl. *psi.*	3115	1875	1300	885	600
Tensile Strength Briquettes, *psi.*	435	385	310	250	175
Drying Shrinkage *percent*	.074	.056	.059	.059	.060
Modulus of Elasticity (Sonic Method)	2.27×10^6	2.24×10^6	1.97×10^6	1.71×10^6	1.29×10^6
Thermal Coefficient of Expansion per deg. F.	2.14×10^{-6}	2.06×10^{-6}	1.93×10^{-6}	1.65×10^{-6}	1.68×10^{-6}
No. Specimens Tested	31	36	36	30	27

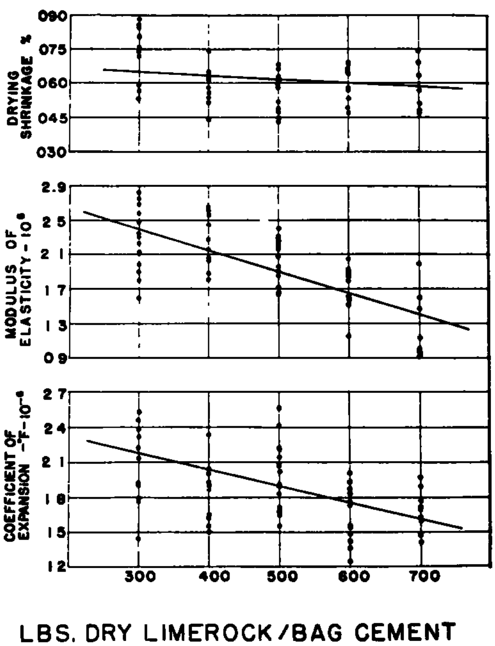

Figure 3. Properties of Plain Limerock Mortar

PLAIN LIMEROCK CONCRETE

Batching—Difficulties have been encountered in discharging limerock from batching bins since the limerock has a tendency to stick together and clog the openings. Employees of the Florida State Road Department have suggested that a larger or different type discharge gate on the batching bin or a vibrator on the bin might remedy this trouble.

The total moisture in limerock when batched should always equal or exceed the absorption of the limerock to insure the presence of adequate water to react with the cement and to prevent changes in the consistency of the concrete while being placed. With the above exceptions, batching of limerock does not differ from the batching of conventional aggregates.

The water, in excess of that absorbed by the aggregate which must be added to limerock concrete mixes to obtain approximately a 4-in. slump, is shown in Table 5.

Mixing and Workability—There is such a preponderance of fine material in 1-in. crusher-run limerock that even in lean concrete mixtures an excess of mortar is produced. Finishing is simplified and honeycombing is reduced to a minimum even for intricate members. For most purposes to control the workability it is only necessary to control the consistency or water content. The slump test is a sensitive indicator of the consistency. Due to the presence of the excess mortar, only slight changes in the water content produce significant changes in the consistency.

Some difficulty has been experienced in finishing the surface of limerock concrete because of its stickiness. This problem is similar to one encountered in finishing air-entrained concrete which is also very sticky. In the case of air-entrained concrete for pavements the problem was solved by increasing the number of transverse oscillations of the screeds per foot of forward motion.

Trouble has been encountered in mixing limerock concrete because it stuck to the blades of the mixer and the materials formed balls. This trouble can be reduced if the mixer is charged in the following sequence: water, aggregate and cement. This not only allows the water to wash previously mixed concrete from the blades of the mixer, but also washes dust coatings from the aggregate particles so that they may be coated directly with cement paste.

Tests were performed to determine what effect prolonged mixing might have on lime rock concrete. This test was made by filling a 3½-cu. ft. Smith mixer to capacity and at regular intervals discharging a sufficient quantity to make a slump test and a 6- by 12-in. cylinder. The results of two such tests were in good agreement and the average test results are listed in Table 3. Prolonged mixing produces slightly less increase in compressive strength for limerock mixes than for conventional aggregate concrete.

TABLE 3
EFFECT OF MIXING TIME ON LIMEROCK CONCRETE STRENGTH

Mixing Time	Percentage of Slump at 3-min. Mixing	Percentage of Strength at 3-min. Mixing
Min.		
3	100	100
6	117	100
10	138	100
15	142	102
20	150	102
30	144	103
40	129	103
60	106	104

TABLE 4
RELATIONSHIP OF SLUMP TO 28-DAY COMPRESSIVE STRENGTH FOR LIMEROCK CONCRETE

	Mix (by wt.)				
	94:300	94:400	94:500	94:600	94:700
Slump Range					
1 to 3 in.	3970	3320	2360	1830	1590
3 to 5 in.	3990	3040	2390	1720	1680
5 to 7 in.	3610	3120	2300	1550	1180

Moisture Control and Water Requirements—Research, to date, indicates that if the cement content of limerock concrete mixes is held constant, the decrease in strength produced by increasing the consistency from a slump of 1 in. to a slump of 7 in. is not significant for the richer mixes. Results contained in Table 4 show that in three of five cases concrete with a 3 to 5 in. slump had the highest compressive strength.

Entrained Air—There appears to be no unusual trend for limerock concrete to entrap air. Tests were performed on unhardened limerock concrete mixes, varying from 94:300 to 94:700 using a pressure meter. Although air contents of as much as four percent were obtained, practically all the air was found to be inside the aggregate particles.

Bleeding and Segregation—No unusual features have been observed concerning bleeding, or water gain, of the mix. Mixtures tested compare favorably with conventional concrete. The stickiness of limerock concrete mixes seems to retard any tendency toward segregation. Observations of mixes vibrated on a 30-in. concrete flow table indicate that all mixes tested would be free from segregation.

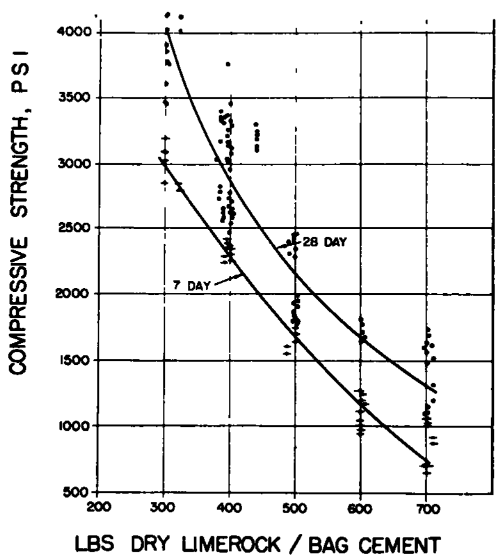

Figure 4. Compressive Strength of Limerock Concrete vs. Weight of Dry Limerock per Bag of Cement

It is doubtful if segregation could be unintentionally produced.

Unit Weight—The weight per cubic foot of limerock concrete is only 85 to 90 percent as great as conventional concrete. The weight varies slightly with the richness of the mix as follows:

Mix by weight	Weight
	lb. per cu. ft.
94:300	132
94:400	131
94:500	130
94:600	129
94:700	129

HARDENED LIMEROCK CONCRETE

Compressive Strength—Probably the most used physical property of hardened concrete is the compressive strength. The compressive strength is used not only to indicate what load a member will carry in direct compression, but also as an indication of the elasticity of the material, the bonding stress which it will develop with steel, the stress it will take as a beam and its strength in shear. Results obtained from 7- and 28-day compressive strength tests for 6- by 12-in. cylinders are shown in Figure 4. A comparison of the strengths obtained from these mixes with expected strengths of concrete made with conventional aggregates reveals that limerock concrete is only about 70 percent as strong as conventional concrete with a similar cement content. This is probably due to the fineness and the lower crushing strength of the limerock aggregate.

From Figure 4 it is seen that the 7-day compressive strength of limerock concrete is approximately 75 percent of the 28-day compressive strength. Additional data have been collected on the age-strength relationship. Tests were conducted on batches containing 94 lb. of cement combined with 400 lb. of oven dry limerock using 6- by 12-in. cylinders. The following average results were obtained:

Age When Tested	Percentage of the 28-day Compressive Strength
1 day	30
3 days	60
7 days	80
14 days	90
21 days	95
28 days	100

Results compiled by the Bureau of Reclamation showing the effect of age on concrete strength made with 10 standard cements and conventional aggregate gave the following average results: (*11*)

Age When Tested	Percentage of the 28-day Compressive Strength
3 days	47
7 days	71
28 days	100

A comparison of these results shows that limerock concrete does gain strength at a more rapid rate and therefore prolonged curing is not as beneficial for limerock as for conventional concrete. A summary of the test results and mix data is given in Table 5.

Modulus of Rupture—The modulus of rupture, or flexural strength, is a measure of the strength of a plain concrete beam or prism in bending. The modulus of rupture is used by the highway engineer to determine the required thickness of a pavement. Results obtained from 78 tests on 6- by 6-in. beams broken over an 18-in. span are given in Figure 5. A modulus of rupture of 500 psi. is normally required before a concrete pavement is opened to traffic. If this were a requirement, only those mixes containing less than 350 lb. of limerock per bag of cement would be satisfactory even when cured under optimum conditions. For conventional aggregate concrete the modulus of rupture is usually 15 to 20

TABLE 5
MIX DATA AND TEST RESULTS FOR LIMEROCK CONCRETE

Mix (by wt.)	No. Batches	Cement Factor	Water-Cement Ratio	Avg. Slump	28-Day Compressive Strength
		bags per cu. yd.	*gals. per bag*	*in.*	*psi.*
94:300	6	7.6	5.3	3.9	4000
94:400	17	6.1	6.1	3.8	2900
94:500	8	5.0	7.6	4.0	2150
94:600	6	4.2	9.1	4.5	1700
94:700	7	3.7	9.6	4.5	1300

percent of the compressive strength. In the case of limerock concrete, the modulus of rupture varied from 13 percent of the compressive strength for rich mixes to 21 percent for lean mixes.

Modulus of Elasticity—The modulus of elasticity of concrete is the ratio of the unit stress in pounds to the unit strain in inches per inch. In the design of reinforced concrete it is necessary to determine the elasticities of both the steel and the concrete in order to know the ratio of the stress distribution between the two materials. No standard procedure has been established for determining the modulus of elasticity of concrete although a compressometer is frequently used. Tests were performed on 6- by 12-in. cyclinders which were moist cured for 28 days followed by air drying at 75 to 85 deg. F. for two to ten weeks. The strain was measured over a gage length of 10 in. Cylinders were repeatedly loaded until no significant plastic flow occurred before they were tested for elasticity. The secant modulus at 0.45 of the 28-day compressive strength was used as the modulus of elasticity. In practically all cases the stress-strain curve was a straight line to stresses of 0.45 of the 28-day compressive strength. Results obtained for 43 stress-strain tests versus the ultimate compressive strength of the concrete at a similar age and moisture content are contained in Figure 6.

The Joint Committee (*10*) suggests that when the modulus of elasticity of concrete is unknown a value of 1000 times the 28-day

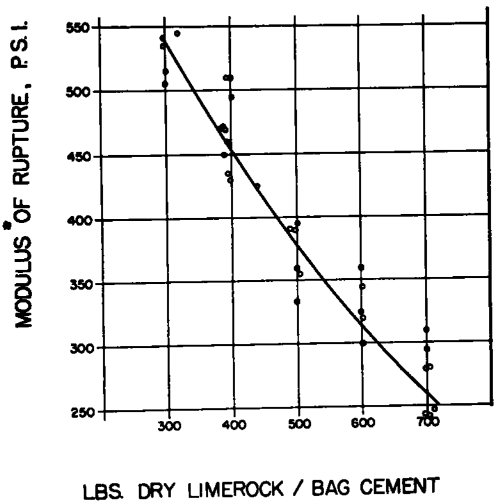

Figure 5. Modulus of Rupture of Limerock Concrete vs. Weight of Dry Limerock per Bag of Cement

compressive strength may be used. Results from these tests would indicate that for lean mixes the modulus of elasticity is 1000 times the compressive strength but for rich mixes the ratio decreases to 600.

Shrinkage—A concrete member changes volume due to changes in both chemical composition and moisture content. It is necessary to know the magnitude of these changes in order properly to control unsightly cracking, ingress of water and even to prevent rupture of the member itself. The coefficient of drying shrinkage for plain limerock concrete has been determined and the results are shown in Figure 7. The drying shrinkage was greater for rich mixes than for lean ones and had an average value of approximately 0.06 percent which is about normal value for conventional concrete.

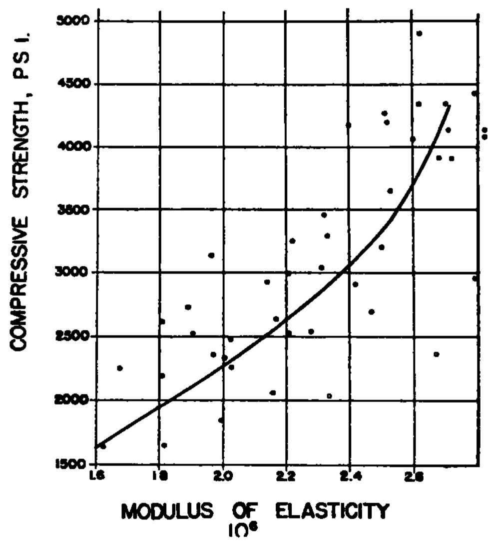

Figure 6. Modulus of Elasticity of Limerock Concrete

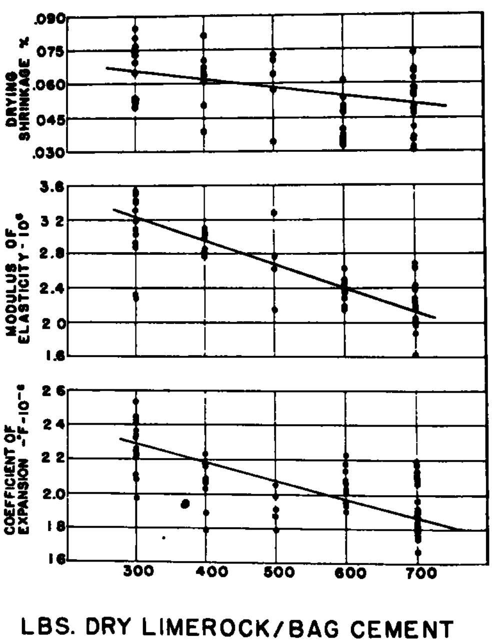

Figure 7. Properties of Plain Limerock Concrete

Coefficient of Expansion—Concrete is generally assumed to have a coefficient of expansion approximately equal to that of reinforcing steel or about 0.000006 in. per in. per deg. F. Under such conditions a uniform temperature change would induce no stresses in a reinforced concrete member. Results compiled by the Bureau of Reclamation (*11*), representing works by eleven investigators, give the following average values for the coefficient of expansion of concrete made with conventional concrete aggregates:

Mix (by wt.)	Coefficient of Expansion per deg F.
1-3	5.8×10^{-6}
1-4	5.6×10^{-6}
1-5	5.4×10^{-6}
1-6	5.3×10^{-6}
1-7	5.2×10^{-6}

Tests have been performed on 53 2- by 2- by 11⅜-in. limerock concrete prisms of various cement content. Each prism was subjected to nine cycles of heating over a temperature range of 70 to 212 deg. F. The data are plotted in Figure 7 and show that the coefficient of expansion increases slightly with increases in the cement content. The average value for all tests was approximately 2.1×10^{-6} or about one-third that of reinforcing steel. To determine what effect the low coefficient of expansion would have on reinforced concrete, reinforcing bars of various sizes were embedded in 2- by 2- by 11⅜-in. prisms. After the concrete had cured for 28 days, the prisms were subjected to repeated cycles of heating to 212 deg. F. and cooling to room temperature. Transverse cracks appeared in every prism following the first cycle of heating regardless of the cement content of the concrete or the size of the reinforcing bar. Both plain and deformed bars were tested. The larger diameter bars produced more transverse cracks than did the smaller ones as shown in Table 6. The coefficient of expansion of reinforced limerock concrete prisms was less than that of steel but greater than plain limerock concrete and increased with increases in the size of the reinforcing bar.

As a further check on the effect of the low coefficient of expansion, limerock concrete beams 6 by 6 by 34 in. were cast into which two ⅜-in. longitudinal reinforcing rods were embedded using a concrete bottom cover of one inch. After curing 28 days at a temperature of 70 deg. F. and 90 percent humidity, the beams were subjected to alternate cycles of heating to 150 deg. F. and cooling to room temperature. These beams began cracking transversely along the bottom surface during the first cycle of heating. Cracks continued to develop for 5 cycles until an average of 6 cracks extending to the mid-depth of the beam had formed.

Although the low coefficient of thermal expansion of limerock concrete may be detrimental to its use in reinforced concrete, it may be advantageous for paving concrete. Concerning a concrete with a low coefficient of expansion, Moyer (*12*) writes:

TABLE 6
EFFECT OF TEMPERATURE CHANGE ON REINFORCED LIMEROCK CONCRETE

	Mix (by wt.)				
	94:300	94:400	94:500	94:600	94:700
½-in. round Bar					
Avg. No. Cracks	4	4	3	2	3
Coef. of Exp. (10^{-6})	4.58	4.98	4.70	4.22	4.68
⅜-in. round Bar					
Avg. No. Cracks	4	3	3	3	3
Coef. of Exp. (10^{-6})	5.13	4.92	4.13	4.20	4.24
¼-in. round Bar					
Avg. No. Cracks	3	3	2	1	2
Coef. of Exp. (10^{-6})	3.74	4.03	3.85	3.58	3.89

"The low thermal coefficients obtained for concrete using this coarse aggregate (Alden, Iowa limestone) and the low modulus of elasticity also obtained for it by the Iowa State Highway Department provides a plausible explanation for the excellent record of this aggregate for freedom of cracking failure and blowups on large concrete pavement projects in Iowa where this aggregate has been used."

BOND BETWEEN REINFORCING BARS AND LIMEROCK CONCRETE

Types of Bond Specimens—There are two general types of specimens that have been used in previous bond studies, beam type specimens and pull-out specimens. Gilkey, Chamberlin and Beal (*13*) in their studies showed that there is close correlation in bond strength obtained by beam tests and pull-out test. Because pull-out specimens are easier to cast, simpler to test, and results can be more readily interpreted, pull-out tests have been used in the majority of bond studies. This type of specimen was used in the study reported herein. The sizes and types of reinforcing bars used were ⅜ in. and ½ in. round, plain and deformed. These were standard bars obtained locally on the commercial market. The deformed bars were of the type with lugs running longitudinally. This type of deformed bar showed lowest bond strengths for the various types of deformed bars in the study of Menzel (*14*) and Clark (*15*). However, this is the type being used in the majority of reinforced work in this area, and as such was considered the logical type for the tests.

The specimens cast had embedment lengths of 4, 6, and 12 in. The specimens were 4 by 4 in. in cross section. They were cast in easily assembled and disassembled forms. Cast specimens are shown in Figure 8. The specimens were left in the forms for approximately 24 hr. after casting. They were then removed from the forms and buried in damp sand at a temperature of 75 to 85 deg. F. until time for testing. Cylinders for 28-day compressive tests were cast at the same time as the pull-out specimens. Care was taken in the design of the forms so that the bars would be held rigid and true with the centerline of the specimen. All specimens were cast vertically.

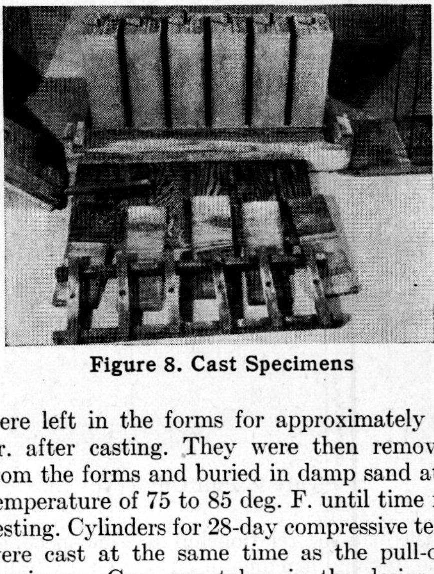

Figure 8. Cast Specimens

Test Procedure—Common procedures were used in the pull-out tests. The reinforcing bars were threaded at their ends prior to casting. Then by means of a special adapter the bar was securely gripped in the testing machine. The compression end of the specimens rested on a spherical bearing block having a one-inch diameter hole in the center for the reinforcing bar to pass through. A bracket was attached to the top of the specimen. This bracket held in place, directly in line with the end of the reinforcing bar extending through the concrete, a steel rod of the same diameter as the reinforcing bar. For measuring slip at the unloaded end, a Modified Templin Snap-on extensometer was attached to the clamped rod and the extended reinforcing bar. Slip of the reinforcing bar with respect to the concrete block at the unloaded end actuated the extensometer. This movement was then automatically recorded by the stress-strain recorder which was attached to the testing machine. An accurate record was thereby made

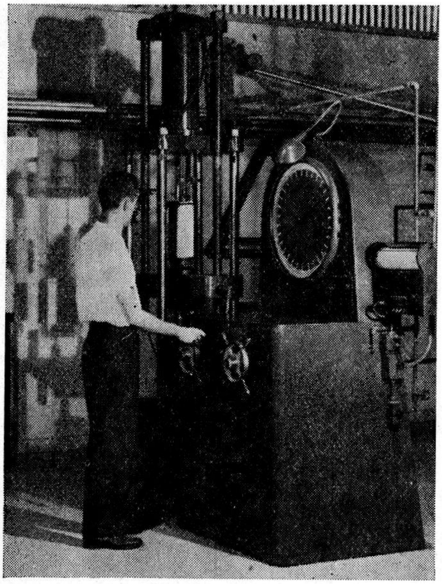

Figure 9. Pull Out Test

of the load-slip relationship for each specimen. The testing machine used was a hydraulic Baldwin Southwark Model 60-35. Figure 9 shows a pull-out specimen in the testing machine. All pull-out tests were conducted 28 days after casting.

RESULTS OF STUDY

Bond Strength Vs. Curing Time—The compressive strength of concrete increases with age. In this study the bond strength obtained at 7 days cure is compared with that obtained at a 28-day curing period. Figure 10 shows the results of this comparison. Five specimens for both curing periods were cast from the same batch. Figure 10 shows that there is no appreciable difference in bond strength between the 7-day and the 28-day cure. Generally speaking, the 28-day bond strength for 12-in. embedment was slightly greater than the 7-day. The results would indicate that there is no danger from lack of bond strength in subjecting reinforced concrete members to dead loads and small live loads at an early age, as is often done in construction practice.

Bond Strength Vs. 28-day Compressive Strength—The 1948 Joint Committee Code (*10*) allows a working bond stress of $0.04f'_c$ for plain bars and $0.05\,f'_c$ for deformed bars, where f'_c is the

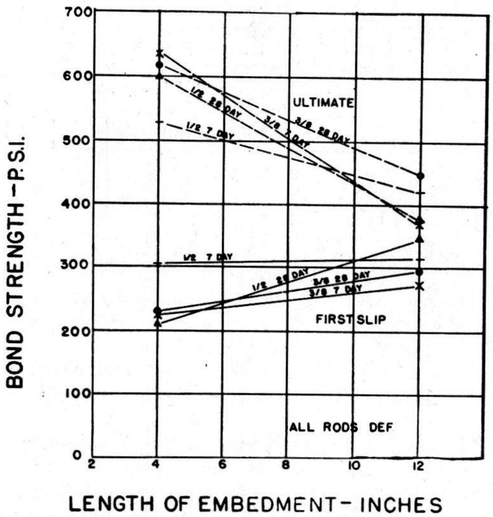

Figure 10. Bond Strength vs. Length of Embedment

28-day compressive strength of the concrete. The limiting bond value for these two types of bars are 160 and 200 psi. respectively. This requirement then suggests that the bond strength is directly proportional to 28-day compressive strength, up to a concrete compressive stress of 4000 psi. The results of tests reported herein do not substantiate this suggested ratio. Neither do the results reported by Gilkey, Chamberlin and Beal (*13*). Figure 11 shows the relationship between bond stress and 28-day compressive stress for $\frac{3}{8}$-and $\frac{1}{2}$-in. diameter bars. The results show that there is an increase in bond stress with an increase in compressive stress of the concrete but the increase is at a much lower rate than is suggested by the Joint Committee Code. The increase in first slip is at a lower rate than that for ultimate bond stress. This would be expected as it is considered that the first slip bond stress is derived mainly from adhesion between the steel and concrete, and at ultimate strength the frictional resistance and lug action (for deformed bars) constitutes the derived bond strength. This discrepancy between test results and Code bond limits has been pointed out by most investigators of bond.

Plotted on the test results as given in Figure 11 are the Joint Committee Code (*10*) limitations increased by a factor of safety of first slip and near the ultimate strength of the steel at ultimate bond stress for those specimens of 12-in. embedment lengths. In fact, failure of the reinforcing bar occurred before ultimate bond strength was reached in two of the specimens. These specimens were included in first slip results but not in the results for ultimate.

Figure 12 shows the ratio of unit bond strength to f'_c plotted against f'_c. The plotted points show that as f'_c increases, the ratio of bond strength to f'_c decreases. This, of course, results in a varying factor of safety over the ranges of compressive sterngth in the concrete. This figure shows that the bond

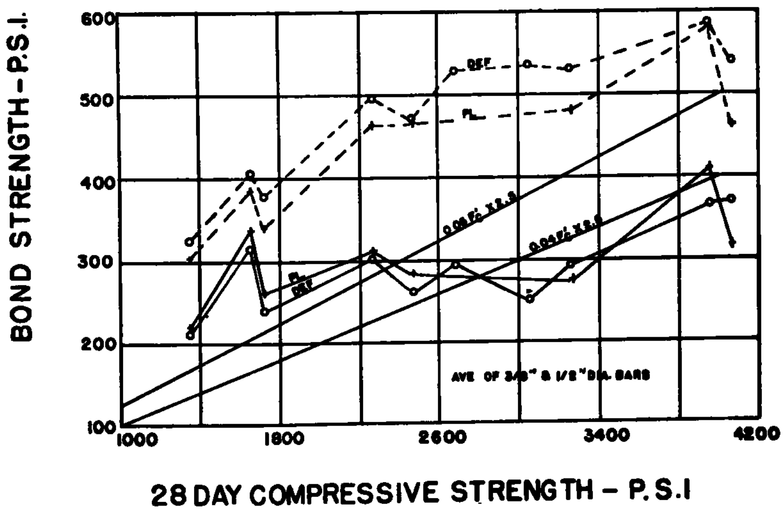

Figure 11. Bond Strength vs. Compressive Strength

2.5. It is seen that the factor of safety on results reported herein at low values of f'_c is considerably above 2.5, while at higher values of f'_c, the factor of safety on first slip is about 2.5 for plain bars but less than this for dedeformed bars. The plotted values show that the difference between plain and deformed bars is not as great, for limerock concrete, as the Code indicates it might be. This is true for ultimate values as well as those at first slip. The curves do show a factor of safety based on ultimate of greater than 2.5 for all ranges of f'_c.

It is noted that there is a sudden drop in bond strength for the 4050-psi. concrete. This can partially be attributed to the fact that the stress in the bar was over the yield point at strengths as found from tests reported herein contain a minimum factor of safety based on the Joint Committee Code (*10*) for plain of 2 for first slip and 3 for ultimate. The factor of safety for deformed bars conformed to these values with the exception that for values of f'_c above 2800 psi., the factor of safety based on first slip was slightly under 2.

Also shown on Figure 12 are some results from the investigations of Gilkey, Chamberlin, and Beal (*13*) conducted using conventional aggregate concrete. These were the only other published results of bond tests in which sufficient results were given, or in which test conditions were sufficiently similar to give a good comparison. The study in Reference 13 did not cover as wide a range of concrete compressive strengths as the study reported herein. The results from Reference 13 show a very close comparison with this study for the ultimate bond strength of plain bars. The "first slip" values from Reference 13 are considerably higher than those from the limerock concrete study. This is to be expected as the definitions for "first slip" are not the same. The study contained herein used the actual first slip of the rod at the unloaded end, while Gilkey, Chamberlin, and Beal (*13*) used an arbitrary definition of 0.0001-in. movement of the unloaded end. The load slip curves from the stress-strain recorder showed that there was a considerable increase in load in most cases from the point of actual first slip to a slip of 0.0001 in. There were insufficient points for deformed bars from Reference 13 to make any comparison.

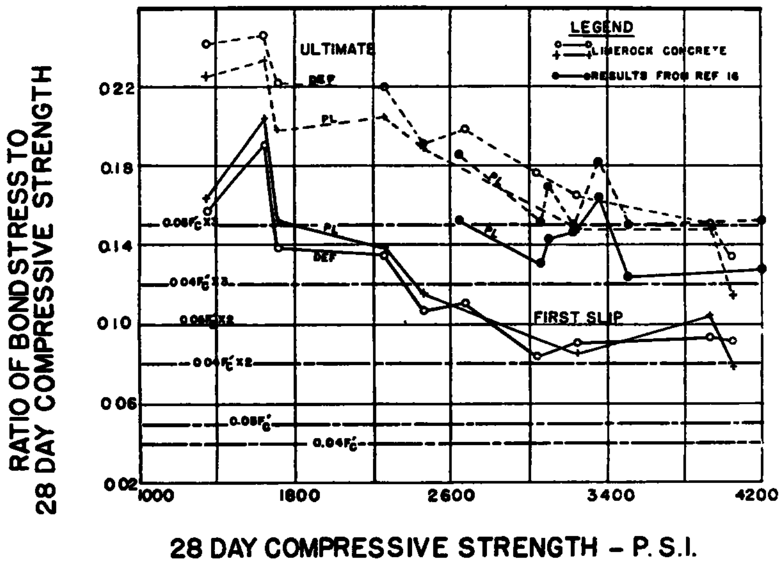

Figure 12. Bond Strength: Compressive Strength Ratio vs. Compressive Strength—f'_c = Compressive Strength

LIMEROCK CONCRETE PAVEMENT

Location and Construction Features—In an effort to determine if limerock concrete could be successfully used in a concrete pavement the Florida State Road Department constructed 4500 lineal feet of pavement 22 ft. wide in November 1944. The project was located on US Highway 441 north of the junction of Ninth Street and Alabama Street. just outside of the Gainesville city limits. Variables investigated included three cement factors, three pavement thicknesses, vibration, and joint spacing. The construction was performed by the Duval Engineering Company of Jacksonville under the direction of the State Road Department Division of Tests.

The concrete pavement replaced a penetration macadam surface with a limerock base. The old pavement was removed and the new pavement so placed that it rested on only three types of soil; dark grey sand, light grey sand, and a brown hardpan. Soil bearing tests were made and only a portion of one section had a Florida bearing value of less than the required thirty-five psi. This low bearing section received additional stabilization with limerock until it had an acceptable bearing value. The 4500 ft. of concrete pavement was constructed using pavement thicknesses of 8–6–8, 9–7–9, and 10–8–10-in. With each pavement thickness cement factors of five, six and seven bags per cubic yard were used. Using pavement of a given thickness and cement content, sections were placed with and without the use of a vibratory paving tube. All non-vibrated sections and 100 ft. of the vibrated sections were placed with dummy joints at 15-ft. intervals. All other dummy joints were placed at 20-ft. intervals. Expansion joints were placed at 200 and 300 ft. Dummy joints were ⅜ in. wide, and expansion joints were ¾ in. wide. Dowels at the transverse joints consisted of ¾-in. plain round bars placed at the mid-depth of the slab 12-in. center to center having one end wrapped with 50-lb. kraft paper. Dowels at the longitudinal joints consisted of ½-in. round deformed bars 4 ft. long placed at the mid-depth of the slab 5 ft. center to center.

Limerock Concrete—Florida portland cement was used in this construction. Crusher-run Ocala limerock was supplied by the Newberry Limerock Corporation. The limerock was crushed so that 100 percent passed the 1½-in. sieve and 73 percent passed the No. 4 sieve. The fineness modulus of the crusher-run material was 3.43. The concrete mixtures were designed for 5, 6, and 7 bags of cement per cu. yd. of concrete or approximately 500, 400 and 325 lb. of dry limerock per bag of cement respectively. The slump was 1½ to 2-in. for the vibrated sections and 2 to 3 in. for the non-vibrated sections. The compressive strength of the vibrated concrete when cured for 28 days in a moist room varied from 3530 psi. for the rich mixes to 2490 psi. for the lean mixes. The non-vibrated concrete was approximately three percent weaker than that which was vibrated. The modulus of rupture of the field specimens was approximately 17 percent of the 28 day compressive strength.

Condition Surveys—Representatives of both the State Road Department Division of Tests and the College of Engineering have made periodic inspections of the limerock concrete test road. A survey conducted by the Traffic and Planning Division of the State Road Department in 1949 revealed a 24-hr. annual average traffic volume over this pavement of 2615 vehicles. The first transverse cracks and spalled joints were reported in the thin sections with the high cement factor in December 1946. It was thought that since this was the first concrete placed on the project that a lack of proper technique was responsible. Since that time cracking of the slabs and spalling of the joints has been progressive especially in the sections with a cement content of seven bags per yard of concrete.

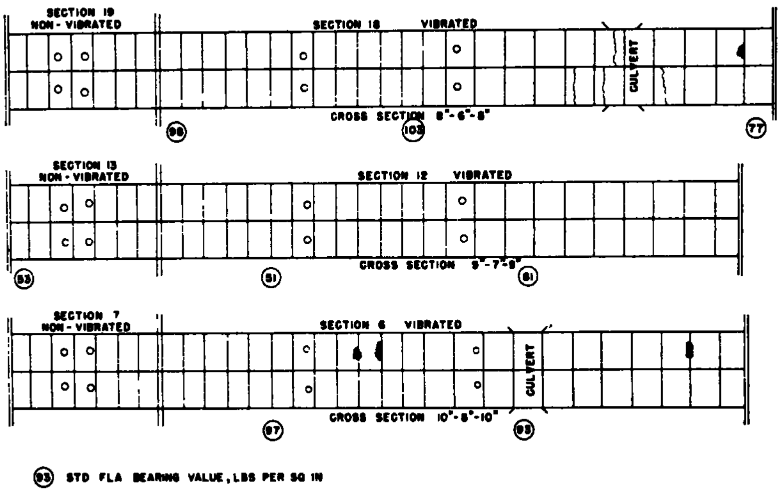

Figure 13. Condition Survey Record—Nov. 1949—Cement Factor = 5

A detailed condition survey was made of the limerock concrete test road in November 1949 at which time the sections containing five bags of cement per yard of concrete were found to be as indicated in Figure 13. It should be emphasized that these sections were not placed continuously, there being intervening sections of the same thickness but with increased cement factors. The circled numbers represent the Florida bearing value for the finished subgrade. The small circles represent core holes. There were only four broken slabs in the six sections constructed with a cement factor of five and these were located near a culvert. The edges of six slabs have spalled.

edges. Slightly more than half of these defects occurred in the thin 8–6–8-in. sections of pavement which represent the first two sections placed on the project.

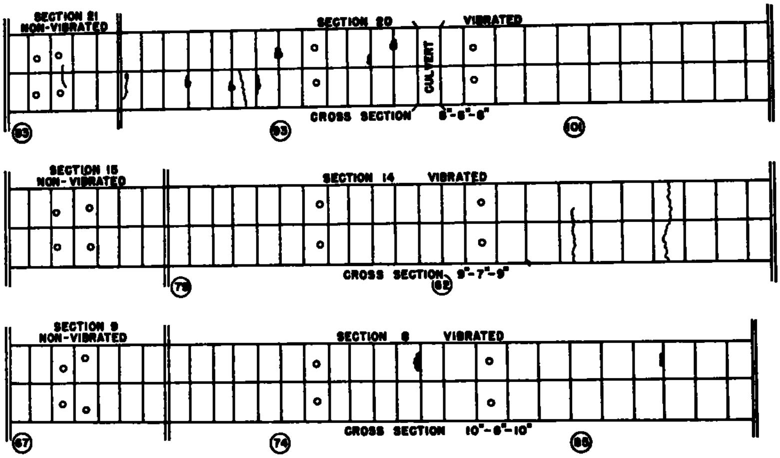

Figure 14. Condition Survey Record—Nov. 1949—Cement Factor = 6

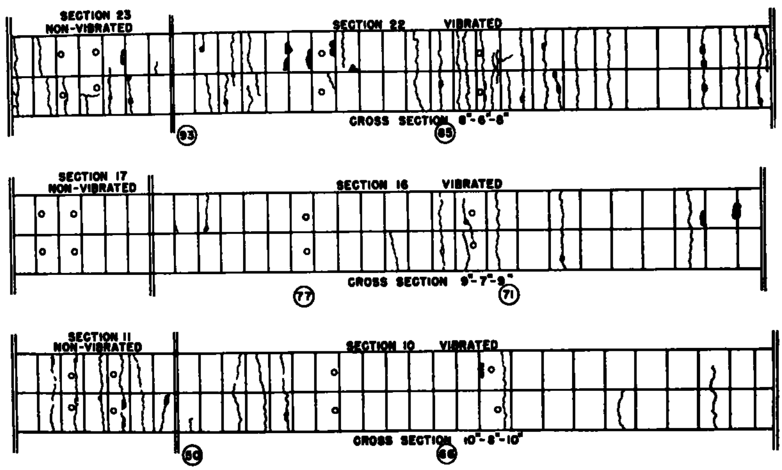

Figure 15. Condition Survey Record—Nov. 1949—Cement Factor = 7

Figure 14 shows the defects observed in six sections in which a cement factor of six bags per yard was used. There were a total of eight broken or cracked slabs and twelve spalled edges.

Figure 15 shows the defects observed in the six sections in which a cement factor of seven bags per yard was used. There were a total of 88 transverse breaks or cracks and 16 spalled edges.

RESULTS AND CONCLUSIONS

1. Limerock aggregate does not comply with the specifications of the American Society for Testing Materials for concrete aggregate.

2. When batched, it appears to be particularly important that limerock should contain a quantity of water equal to or greater than the absorption of the limerock.

3. Limerock concrete with a 4-in. slump requires approximately 38 gal. of free mixing water per cubic yard of concrete when crusher-run aggregate is used.

4. Limerock concrete develops a 28-day compressive strength of approximately 70 percent of that developed by a concrete mixture containing a similar amount of cement, a medium hard limestone aggregate and an equal consistency.

5. Limerock concrete develops a 28-day modulus of rupture varying from 13 percent of the 28-day compressive strength for rich mixes to 21 percent for lean mixes.

6. The modulus of elasticity of limerock concrete varies from 1000 times the compressive strength for lean mixes to 600 times the compressive strength for rich mixes.

7. The average drying shrinkage of limerock concrete is approximately 0.06 percent and compares favorably with conventional aggregate concrete.

8. The coefficient of thermal expansion for limerock concrete is approximately one-third that of reinforcing steel.

9. The working strength for bond using limerock concrete can be that given in the 1940 Joint Committee Code.

10. The bond strength using limerock concrete is practically fully developed at the end of 7 days.

11. The present condition of the limerock test road would indicate that the most durable pavement was produced with the concrete containing five and six bags of cement per cubic yard. The transverse cracks seem to be independent of the subsoil, vibration and joint spacing.

12. Data obtained to date in the laboratories of the Civil Engineering Department of the University of Florida do not indicate that the leaner mixes of limerock concrete should have added resistance to transverse cracking insofar as stress produced by temperature and drying shrinkage are concerned.

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