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Concrete Containing Marginal Aggregates for Use in Concrete Pavement

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Abstract: The study presented an analysis accessing the feasibility of using concrete containing marginal aggregates in concrete pavement slabs. The physical properties of aggregates were first determined and concrete was produced from them. Marginal aggregates were found to have higher fines, absorption, soundness loss, micro-Deval abrasion loss, LA (Los Angeles) abrasion loss and lower specific gravity and unit weight when compared with standard aggregates. Workability of concrete containing marginal aggregate was found to be similar to concrete containing normal aggregates when Shilstone mix design method was used to optimize the concrete mixes. The compressive strength, splitting tensile, flexural strength and modulus of elasticity of concrete containing marginal aggregates were determined and found to be generally lower than concrete containing standard aggregates. A typical concrete pavement in Florida was modeled in FEACONSIV (finite element analysis of concrete slab) software developed at the University of Florida. Laboratory determined mechanical and thermal properties of concrete were inputted in FEACONS IV and analyzed for maximum induced stresses. Critical stress to strength ratios, i.e., ratio between maximum computed stresses obtained from FEACONS IV to modulus of rupture (strength) of concrete, was used as evaluation criterion for different concrete pavement mixes. It was found that, in general, concrete containing marginal aggregates have higher stress to strength ratios as compared with concrete containing standard aggregates.

Key words: Marginal aggregates, concrete, pavement, stress to strength ratio, FEACONS.

1. Introduction

Concrete is generally thought of as having three components, i.e., aggregate phase, hydrated cement paste and ITZ (interfacial transitional zone) between the hydrated cement paste and the aggregate phase. The aggregate phase is the stronger of the two phases and is predominantly responsible for unit weight, elastic modulus and dimensional stability of concrete. For normal concrete, the aggregate phase mostly has no influence on strength except in the case of highly porous and weak aggregates such as pumice [1]. In view of the above, the strength of aggregate is mostly not taken into consideration when producing normal concrete. However, due to increasing depletion of good quality aggregates, weaker aggregates are now considered to be used for some concrete application, and thus, the need to examine closely the effect of aggregate strength on mechanical and durability properties of concrete produced from them. These weaker aggregates are mostly considered as marginal or borderline aggregates and do not meet current standards and specifications, and in cases where they are allowed, they are used for concrete applications with very low strength. Key among these weak aggregates is natural aggregates that do not meet current standards and specifications.

The classification of aggregates as marginal or borderline is dependent on the standard of comparison. In the US, most aggregates for use in DOT (Department of Transportation) applications must either satisfy ASTM (American Society for Testing and Materials), AASHTO (American Association of State Highway and Transportation Officials), or specific tailored standards, as stipulated in various

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states standard specifications. Thus, an aggregate is considered as marginal when it does not meet the aforementioned standards. Usually, marginal or borderline aggregates fail to meet requirements of gradation, LA (Los Angeles) abrasion loss, soundness loss, shell content, specific gravity, absorption, etc.. These marginal aggregates are generally considered to be weaker, and thus require special attention before incorporating them into concrete mixes.

This paper first compares properties of concrete obtained from marginal aggregates with those obtained from standard aggregates. It proceeds with using the mechanical properties of these concrete as input in a finite element analysis software to predict the possible performance of the concretes if they were used as slabs in concrete pavement.

2. Research Significance

Past research into effect of marginal aggregates on performance of concrete has been limited [2-4]. Furthermore, there is a burgeoning need for the feasibility of using marginal aggregates in most states. If this objective is realized, there will be a potential increase in aggregate mines that were hitherto not accredited to supply aggregates for certain DOT works. Also, existing aggregate mines may increase their production lines hence a general increase in aggregate supply within the United States.

3. Materials and Test Method

This research was conducted in the state of Florida and aggregates were selected with assistance from FDOT (Florida Department of Transportation) personnel. Two currently approved aggregate sources (standard aggregates) and eight non approved sources (marginal aggregates) were identified and used for the research. Table 1 shows a list of different aggregate sources and nomenclature used to identify them in this paper. Sieve analysis was conducted on aggregates in accordance with ASTM C136 [5]. The percentage of material finer than 75 μm sieve was determined in accordance with ASTM C117 [6]. Table 2 shows aggregate gradation. It must be noted that modified Miami oolite (S1) and modified Fort Myers (S2) aggregates were artificially created by adding pulverized fines passing the No. 200 sieve to produce aggregates with a total percentage passing the No. 200 sieve of 5% and 8%, respectively. From the gradation, it is observed that most of the aggregates failed to meet ASTM C33 [7] specification especially on the finer sieves. Specifically, Aggregates S3, S4, S5, S6, S7, S8, and S10 all failed to meet ASTM C33 [7] requirement of 0%-5% on sieve size 2.36 mm. Specific gravity and absorption of aggregates were determined in accordance with ASTM C127 [8]. From Table 3, it can be observed that absorptions of marginal aggregates

Table 1 Identification of aggregate sources.

Aggregate I.D.	FDOT mine #	Nomenclature	Aggregate properties not meeting current standards	Aggregate type
S1	87089	Miami oolite		Standard
S2	12260	Fort Myers		Standard
S3	87089	Modified Miami oolite	Miami oolite with addition of pulverized fines to produce a total of 8% minus 200	Marginal
S4	12260	Modified Fort Myers	Fort Myers with addition of pulverized fines to produce a total of 5% minus 200	Marginal
S5	N/A	Inglis	High minus 200	Marginal
S6	38228	Cabbage Grove	High LA abrasion loss	Marginal
S7	36696	Ocala	High LA abrasion	Marginal
S8	01011	Coral rock	High shell content	Marginal
S9	N/A	Weber south	High shell content	Marginal
S10	08012	Brooksville	High LA abrasion loss	Marginal

Table 2 Results of sieve analysis.

Sieve size (mm)	ASTM C33 gradation requirement	Aggregate source									
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
		Percentage passing (%)									
37.50	100	100	100	100	100	100	100	100	100	100	100
25.00	95-100	100	100	100	100	96	98	93	100	100	99
12.50	25-60	59	30	60	35	48	35	31	66	43	71
4.75	0-10	7	3	10	9	11	6	7	8	3	22
2.36	0-5	3	2	6	9	8	6	6	6	2	17
Minus 75 µm	3.00*	2.20	0.98	5.00	8.00	3.98	3.36	4.08	2.74	0.85	9.22

*Concrete subject to abrasion, all other concrete is 5.0%. In the case of manufactured sand, if the material finer than the 75 µm sieve consists of the dust of fracture, essentially free of clay of shale, these limits are permitted to be increased to 5% to 7%, respectively.

Table 3 Specific gravities and absorption of aggregates.

Aggregate source	Bulk specific gravity (dry)	Bulk specific gravity (SSD (saturated surface dry))	Apparent specific gravity	Absorption (%)
S1	2.35	2.45	2.63	4.54
S2	2.30	2.39	2.54	3.99
S3	2.35	2.45	2.63	4.54
S4	2.30	2.39	2.54	3.99
S5	2.35	2.45	2.59	3.85
S6	2.11	2.27	2.49	7.25
S7	2.12	2.29	2.54	7.80
S8	2.23	2.34	2.52	5.16
S9	2.16	2.32	2.57	7.38
S10	1.82	2.08	2.46	14.38

Table 4 Unit weight, LA abrasion loss, micro-Deval abrasion loss and sodium soundness loss.

Aggregate source	Unit weight (kg/m^3)	Los Angeles abrasion loss (%)	Micro-Deval loss (%)	Sodium soundness loss (%)
S1	1323	31	26	9
S2	1368	36	29	13
S3	1323	31	26	9
S4	1368	36	29	13
S5	1441	42	27	13
S6	1267	50	38	14
S7	1287	46	47	20
S8	1264	40	29	12
S9	1212	48	32	29
S10	1185	67	81	38

are generally high. Unit weight, LA abrasion loss, micro-Deval abrasion loss and sodium sulfate soundness loss were also determined in accordance with AASHTO T19 [9], AASHTO T96 [10], AASHTO T327 [11] and AASHTO T104 [12], respectively. Table 4 shows a summary of these results. ASTM C33 [7] recommends an LA abrasion loss of less than 50%, thus, only Aggregate S10 fails to meet this requirement. However, FDOT specification [13] requires the value to be less than 45%, consequently, Aggregates S6, S7, S9 and S10 fail to meet FDOT specification.

4. Concrete Mix Design

In view of the unique nature of these marginal aggregates, trial mixes were first made using ACI (American Concrete Institute) mix design method [14]. This resulted in a non-workable mix for concrete containing the marginal aggregates. Therefore, the Shilstone method [15, 16], which is based on gradation optimization, was employed to optimize the mixes and this resulted in workable mixes. Concretes of different proportions were produced using Shilstone and ACI design methods for marginal and standard aggregates, respectively. Silica sand from FDOT source 71132 was used as fine aggregate. The specific gravity and absorption of fine aggregates were determined in accordance to AASHTO T85 [17] and the results are shown in Tables 5 and 6. Types A and D water-reducing admixtures complying with ASTM C494 [18] were added to all mixtures to improve their workability. Table 7 shows details of mix proportions and properties of the fresh concrete produced. After fabricating the different samples in accordance with ASTM C192 [19], fresh concrete was cast, de-molded after 24 h and cured for 28 days. The tests performed on the hardened concrete are shown in Table 8. Results of the tests on the hardened concrete are shown in Table 9.

5. Test Results of Aggregate and Fresh Concrete

5.1 Aggregate Test Results

From the results of aggregates testing, the following can be inferred:

Table 5 Specific gravity and water absorption of fine aggregates.

Property	Fine aggregates
SSD specific gravity	2.63
Dry bulk specific gravity	2.62
Dry apparent specific gravity	2.65
Absorption	0.5

Table 6 Results of sieve analysis on the fine aggregate.

Sieve size (mm)	Percentage passing fine aggregates (%)
4.75	100
2.36	99
1.18	91
0.60	70
0.30	32
0.15	5
Fineness modulus	2.03

Table 7 Concrete mix proportions for concrete containing low cement content.

Aggregate source	Water/cement ratio (*w*/*c*)	Mix proportions				Properties of fresh concrete			
		Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Slump (mm)	Unit weight (kg/m^3)	Air content (%)	Temperature (°C)
S1	0.6	991	843	279	167	83	2,231	3.1	24
S2	0.6	967	838	279	167	76	2,229	2.4	24
S3	0.6	991	843	279	167	44	2,213	3.7	25
S4	0.6	967	838	279	167	57	2,216	2.7	27
S5	0.6	989	843	279	167	51	2,227	2.9	24
S6	0.6	926	806	279	167	51	2,167	2.9	23
S7	0.6	897	876	279	167	32	2,168	3.8	26
S8	0.6	934	830	279	167	44	2,224	2.4	21
S9	0.6	936	818	279	167	114	2,172	3.0	24
S10	0.6	806	860	279	167	38	2,103	0.4	24

Table 8 Tests performed on the concrete samples.

Test	Standard	Specimen size	Curing period
Compressive strength	ASTM C39	100 m × 200 mm cylinder	28 days
Elastic modulus	ASTM C469	100 m × 200 mm cylinder	28 days
Flexural strength	ASTM C78	100 mm × 100 mm × 350 mm beam	28 days
Splitting tensile strength	ASTM C496	100 m × 200 mm cylinder	28 days

Table 9 Hardened concrete properties.

Aggregate source	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)	Poisson's ratio
S1	32.54	3.03	4.62	28.35	0.24
S2	31.65	3.17	4.52	27.20	0.27
S3	32.06	3.10	4.65	27.62	0.25
S4	29.65	2.90	4.31	25.70	0.26
S5	26.27	2.69	3.93	22.68	0.22
S6	25.03	2.93	3.72	22.45	0.27
S7	23.99	2.55	3.69	22.75	0.27
S8	28.68	3.34	4.48	25.51	0.25
S9	19.03	2.48	3.52	20.95	0.22
S10	17.17	1.90	2.83	18.16	0.25

Most of the marginal aggregates were finer than standard aggregates. They had higher percentage of materials passing No. 4 and No. 200 sieves.

Marginal aggregates have higher absorption and relatively lower SSD. Their unit weights were comparatively lower than those of standard aggregates.

Marginal aggregates were generally less durable when their LA abrasion loss, micro-Deval abrasion loss and sodium sulfate soundness loss are compared with standard aggregates.

5.2 Fresh Concrete Test Results

From the fresh concrete test results, the following findings were made:

Workability of concrete mixes using marginal aggregates was similar to those using standard aggregates, although they had higher percentages of material passing No. 4 and No. 200 sieves. This is attributed partly to use of Shilstone mix design method which allowed for optimization of aggregate gradation.

Unit weight for mixtures containing marginal aggregates was about the same as mixtures containing standard aggregates with the exception of concrete containing Aggregate S10, which had lower unit weight.

Air content for mixtures containing marginal aggregates was about the same as mixtures containing standard aggregates with the exception of concrete containing Aggregate S10, which had lower air content.

5.3 Discussion on Aggregates and Concrete Test Results

Marginal aggregates are generally finer than standard aggregates and, thus, fail ASTM C33 [7] requirements. Moreover, they have higher absorption, lower specific gravity and higher LA abrasion values when compared with standard aggregates. However, when properly designed, concrete produced from marginal aggregates can have similar workability and air content as concrete containing standard aggregates. Compressive strength, splitting tensile, flexural strength and modulus of elasticity of concrete containing marginal aggregates are generally lower than concrete containing standard aggregates.

6. Evaluation of Potential Performance of Concrete in Pavement

6.1 FEACONS Analysis

FEACONS IV (finite element analysis of concrete slabs version IV) program was used to perform stress analysis. FEACONS IV program was previously developed at the University of Florida for FDOT for analysis of PCC (Portland cement concrete) pavements subjected to load and thermal effects and had demonstrated to be a fairly effective and reliable tool for this type of analysis. Fig. 1 shows the finite element model used to perform stress analysis. The 10 different concrete mixes were analyzed to determine their performance on a typical concrete pavement in Florida.

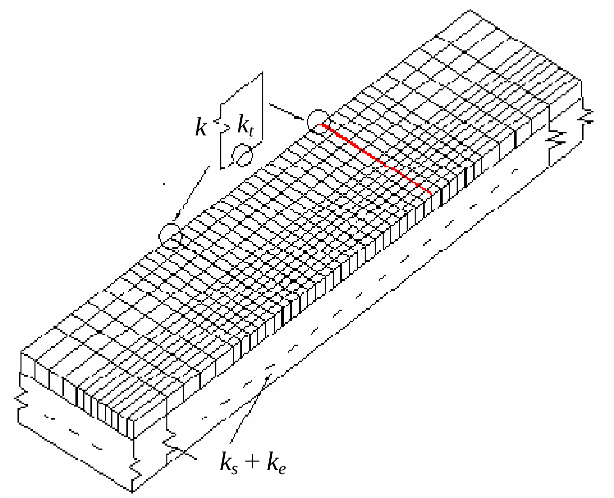

Fig. 1 Finite element model used in FEACONS IV analysis.

The laboratory determined properties in Table 9, i.e., elastic modulus, compressive strength, density and coefficient of thermal expansion, were inputted in the model. Analysis using FEACONS IV model was performed to determine stresses in a 254 mm thick slab. The analysis was performed to determine maximum stresses in a JPCP (jointed plain concrete pavement) slab loaded with a 98 kN wheel applied at critical loading positions, i.e., slab corner and middle edge as shown in Fig. 2. Temperature differentials of +6.67 °C, 0 °C and -6.67 °C in concrete slab were used for the analysis. The middle of slab edge is the most critical loading position in day time when temperature differential in the slab is positive, while slab corner is most critical loading position at night when temperature differential is negative. The following parameters were used to model the concrete pavement:

- slab thickness = 254 mm, slab length = 4.57 m, slab width = 3.66 m;
- subgrade modulus, k_s = 82 MN/m^3, edge stiffness, k_e = 207 MN/m^2;
- joint linear stiffness, k_l = 3447 MN/m^2, joint torsion stiffness k_t = 4.4 MN-m/m.

6.2 Results of Stress Analysis Using FEACONS IV Analysis

Stress distribution and deflection of pavement due to temperature differential and axle loads are the main output from FEACONS IV. For purpose of this study, focus was placed on stress distribution, typical plots of stress distribution are shown in Figs. 3 and 4. The maximum critical stress was determined for each loading and temperature condition. Thereafter, critical stress to strength ratios, i.e., ratio between maximum critical computed stresses obtained from FEACONS IV to modulus of rupture (strength) of concrete was used as evaluation criterion for different mixes. From fatigue theory, a low stress to strength ratio would indicate a higher number of load repetitions to failure and a better performance potential for concrete pavements in the field. Table 10 shows the critical stress to strength ratios at corner and middle edge of slab with + 6.67ºC, -6.67 ºC and 0 ºC temperature differentials.

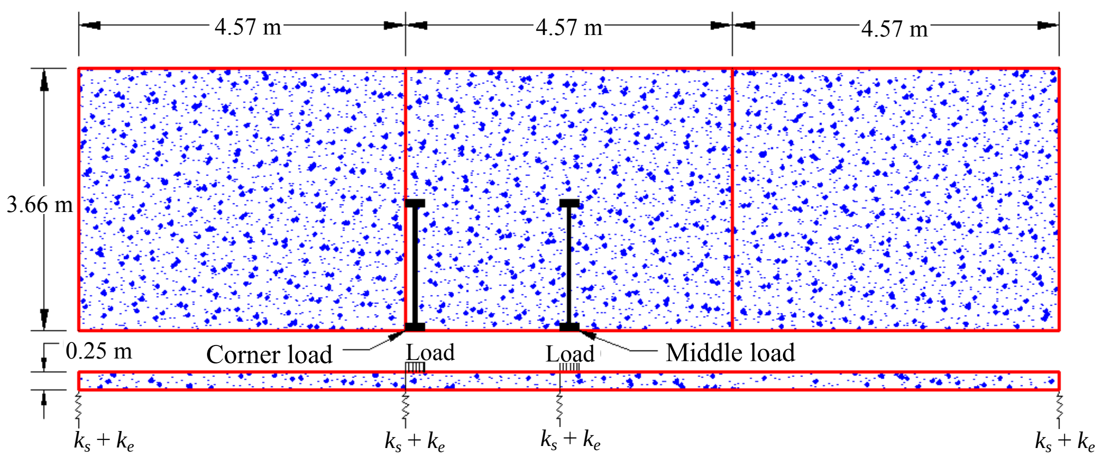

Fig. 2 22-kip wheel load at slab corner and middle edge.

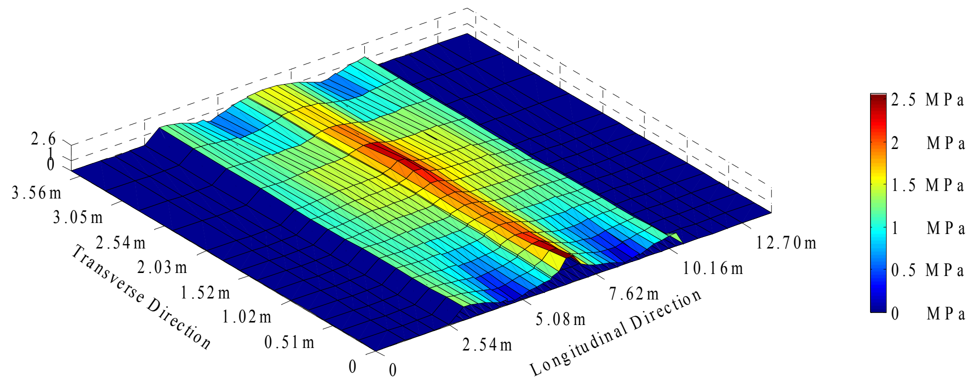

Fig. 3 Typical stress distribution for pavement with positive temperature differential and load at middle edge.

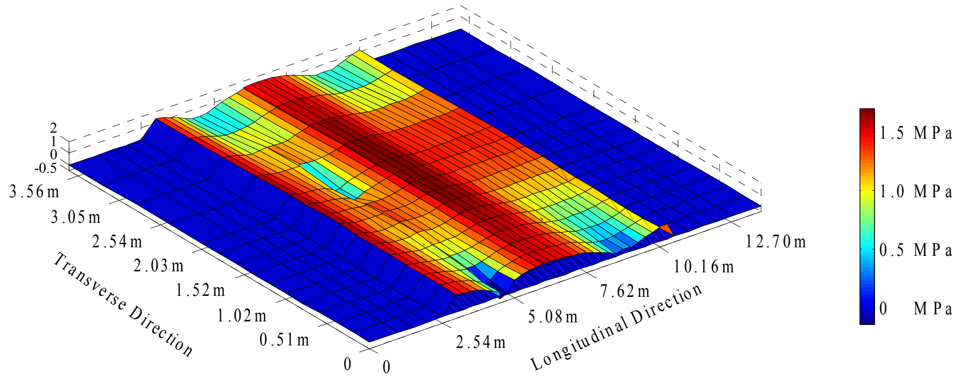

Fig. 4 Typical stress distribution for pavement with negative temperature differential and load at corner edge.

6.3 Observation on Results of Stress Analysis

From results presented in Table 10, it can be seen that the most critical loading condition which results in the maximum computed stress was the condition when the 98 kN axle load was applied at middle edge of the slab, and when temperature differential is +6.67 ºC. Thus, the observation of potential performance of the various concrete mixes will be focused mainly on computed stress to strength ratio at this condition. Fig. 5 shows a plot of concrete containing different sources against stress to strength ratios.

From Table 10, it is also observed that critical stress-strength ratios of marginal aggregates are higher than concrete containing standard aggregates. However, from fatigue theory [20, 21], a stress-strength ratio of less than one indicates that concrete pavement can sustain imposed stresses.

7. Conclusions and Recommendations

This study presented a laboratory testing results of eight marginal aggregates and two standard aggregates. The physical properties of aggregates were first determined and concrete was produced from them. Marginal aggregates were found to have higher fines, absorption, soundness loss, micro-Deval abrasion loss, LA abrasion loss and lower specific gravity and unit weight when compared with standard aggregates. Also, from fresh concrete properties, it can be concluded that when properly designed, concrete produced from marginal aggregates can have similar workability and air content as concrete containing standard aggregates. The compressive strength, splitting tensile, flexural strength and modulus of elasticity of concrete containing marginal aggregates were determined and found to be generally lower than concrete containing standard aggregates.

Table 10 Computed maximum stresses and stress-strength ratios.

Aggregate I.D.	Poisson's ratio	Mean 28-day				Computed stress (MPa)		Stress ratio	
		Water saturated CTE (coefficient of thermal expansion) (10^{-6}/°F)	Compressive strength (MPa)	Modulus of elasticity (GPa)	Modulus of rapture (MPa)	Corner	Middle edge	Corner	Middle edge
Temperature differential = +6.67 °C									
S1	0.24	7.92	32.54	28.34	4.62	2.34	2.52	0.51	0.55
S2	0.27	7.67	31.65	27.19	4.52	2.30	2.43	0.51	0.54
S3	0.25	8.83	32.06	27.62	4.65	2.39	2.63	0.51	0.56
S4	0.26	8.96	29.65	25.70	4.31	2.40	2.54	0.56	0.59
S5	0.22	10.70	26.27	22.68	3.93	2.43	2.56	0.62	0.65
S6	0.27	9.96	25.03	22.45	3.72	2.39	2.48	0.64	0.66
S7	0.27	7.59	23.99	22.75	3.69	2.14	2.19	0.58	0.59
S8	0.25	9.60	28.68	25.51	4.48	2.40	2.54	0.54	0.57
S9	0.22	9.09	19.03	20.95	3.52	2.23	2.30	0.64	0.65
S10	0.25	8.82	17.17	18.15	2.83	2.05	2.03	0.72	0.72
Temperature differential = -6.67 °C									
S1	0.24	7.92	32.54	28.34	4.62	1.11	1.22	0.24	0.26
S2	0.27	7.67	31.65	27.19	4.52	2.30	2.43	0.51	0.54
S3	0.25	8.83	32.06	27.62	4.65	2.39	2.63	0.51	0.56
S4	0.26	8.96	29.65	25.70	4.31	2.40	2.54	0.56	0.59
S5	0.22	10.70	26.27	22.68	3.93	1.71	1.61	0.44	0.41
S6	0.27	9.96	25.03	22.45	3.72	1.66	1.56	0.45	0.42
S7	0.27	7.59	23.99	22.75	3.69	1.30	1.20	0.35	0.33
S8	0.25	9.60	28.68	25.51	4.48	1.65	1.54	0.37	0.34
S9	0.22	9.09	19.03	20.95	3.52	1.45	1.35	0.41	0.38
S10	0.25	8.82	17.17	18.15	2.83	1.22	1.14	0.43	0.40
Temperature differential = 0 °C									
S1	0.24	7.92	32.54	28.34	4.62	1.11	1.22	0.24	0.26
S2	0.27	7.67	31.65	27.19	4.52	1.11	1.22	0.25	0.27
S3	0.25	8.83	32.06	27.62	4.65	1.10	1.21	0.24	0.26
S4	0.26	8.96	29.65	25.70	4.31	1.09	1.20	0.25	0.28
S5	0.22	10.70	26.27	22.68	3.93	1.03	1.14	0.26	0.29
S6	0.27	9.96	25.03	22.45	3.72	1.05	1.16	0.28	0.31
S7	0.27	7.59	23.99	22.75	3.69	1.06	1.17	0.29	0.32
S8	0.25	9.60	28.68	25.51	4.48	1.08	1.19	0.24	0.27
S9	0.22	9.09	19.03	20.95	3.52	1.01	1.12	0.29	0.32
S10	0.25	8.82	17.17	18.15	2.83	0.99	1.09	0.35	0.39

The hardened properties of concrete were inputted in an FEACONS IV to determine critical stress in a typical concrete pavement in Florida. The ratio between the computed critical stresses obtained from FEACONS IV to the modulus of rupture (strength) of concrete was obtained and used as evaluation criterion for potential performance of concrete pavement.

It was found that, critical stress-strength ratio of concrete containing marginal aggregates was higher than that of concrete containing standard aggregates. Thus, concrete containing marginal aggregates will perform poorer than concrete containing standard aggregating this. Notwithstanding, it was found that all critical stress to strength ratios of concrete containing

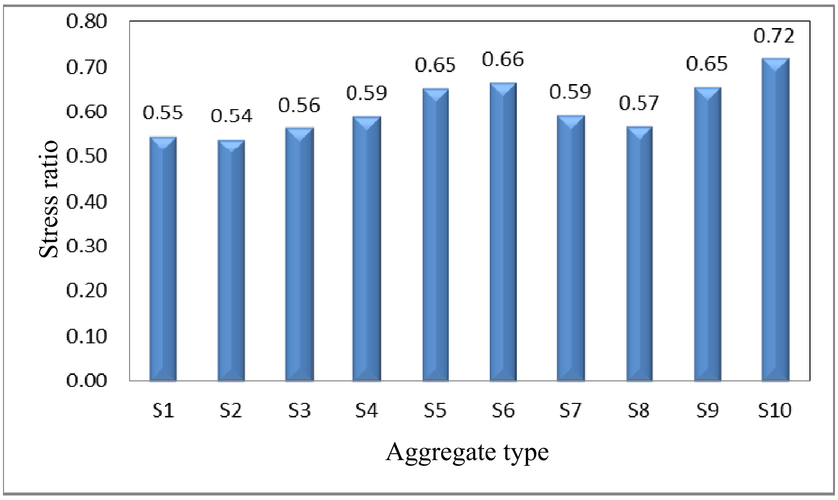

Fig. 5 Plot of the maximum stress to strength ratio vs. aggregate type.

marginal aggregates were less than one. Thus, concrete pavement containing marginal aggregates can sustain imposed stresses. From the forgoing, it can be concluded that when properly designed, concrete containing marginal aggregates can be used successfully as aggregates in concrete pavements.

Therefore, it is recommended that a further study on improving properties of concrete made from these marginal aggregates should be conducted. There is also a need to verify key properties of marginal aggregates that affect properties of concrete in which they are used.

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