A Rapid Green Base Repair CLSM

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ABSTRACT

High-early strength controlled low-strength material mixture designs containing no portland cement were developed using three different fine aggregates (natural sand, manufactured sand, and limestone screenings) for "green" rapid subgrade repair applications under the direction of the Federal Highway Administration (FHWA). An attempt was made to determine if fifty percent by volume replacement of the fine aggregate with ASTM No.67 stone would allow the modified mixtures to function as emergency "green" base repair materials. The substitution of coarse aggregate increased the static modulus of elasticity by an average of 69 and 78 percent at 24 hours and 28 days, respectively. The mixtures achieved a high level of stiffness, with a minimum of 7.9-GPa (1150-ksi) at one day. Further, the mixtures with coarse aggregate substitution had average California Bearing Ratios (CBR) of 83 and 605 percent at 6.5 and 24 hours, respectively. No mixture with coarse aggregate substitution had a CBR less than 55 at 6.5 hours and the mixture with limestone screenings as fine aggregate had a base quality CBR of 129 percent. At 24 hours, the CBRs of the mixtures with coarse aggregate substitution were above 300, far above the typically specified 100 for a good base. Coarse aggregate substitution increased CBR by 324 and 244 percent on average at 6.5 and 24 hours. Finally, average compressive strengths of the mixtures with coarse aggregate substitution were 0.3 and 3.5-MPa (43 and 507-psi) at 4 and 24 hours, respectively.

INTRODUCTION

Controlled low-strength material (CLSM) is a highly flowable, self-compacting, cementitious material that is primarily used as a backfill in place of compacted earth fill (*1*). CLSM is often referred to by a number of different terms or types, including flowable fill, controlled density fill, flowable fly ash, unshrinkable fill, and soil-cement slurry (*1*). It is comprised of water, cement, fine aggregates, and commonly contains fly ash or other industrial by-products, and chemical admixtures. The compressive strength of CLSM is limited to 8.3-MPa (1200-psi), which is much lower than that of normal concrete (*1*). Lower limits on strengths can make future excavation an option if desired (*2*). CLSM is a safe and economical alternative since it can be self-compacting and highly flowable, thus eliminating the need to enter confined spaces and excavation areas to manually compact fill. CLSM is also readily available from ready-mixed concrete producers, easy to place and deliver, and can be proportioned to meet requirements for a wide range of applications (*3*).

CLSM APPLICATIONS

CLSM is used in lieu of backfill for various applications, and the innovative uses are growing every year. Common applications include trench fills, pipe embedment, pavement bases, abandoned underground facilities, structural fills, and bridge approach repairs, to name a few. CLSM has also been used in environment-enhancing applications such as protecting groundwater resources and minimizing problems and damage caused by moving water (*4*).

Rapid-setting CLSM has proven to be an ideal backfill material for use on street repairs and infrastructure rehabilitation projects (*5*). This material has proven to be an ideal subgrade repair for situations in which pavement must be opened to traffic as soon as possible. These rapid-setting materials also have low shrinkage, are economical, are not labor intensive, and can be excavatable if desired (*5*).

RESEARCH OBJECTIVE

The objective of the Federal Highway Administration cooperative agreement, “Rapid Repair of Highway and Airfield Pavement Subgrades with Controlled Low-strength Materials,” was to develop a high-early strength, non-excavatable CLSM that would reduce roadway repair duration, costs, and safety risks. Two versatile, high early strength CLSM mixture designs were developed. One CLSM mixture design was air-entrained with a portland cement binder and one was non-air-entrained with a fly ash binder for sustainability concerns. Both CLSM mixture designs share common performance goals shown in table 1.

TABLE 1 CLSM Mixture Design Performance Goals

Engineering Property	Minimum Performance Goals
Flow (ASTM D 6103-04)	200-mm[b]
Compressive Strength at 4 hours[a]	0.07-MPa[c]
Compressive Strength at 6 hours[a]	0.21-MPa
Compressive Strength at 28 days[a]	2.80-MPa

[a] ASTM D 4832-02 as modified by TDOT 204.06 2006
[b] 1 mm = 0.0394 inch
[c] 1 MPa = 145 psi

Versatility refers to the ability of the basic mixture design to be modified to accommodate different common aggregates. Regardless of the type selected, it is important that a high early strength CLSM mixture design be versatile enough to work with aggregates commonly available across the United States. Therefore, three different aggregates were used in the development of CLSM mixtures from each of the two major design philosophies. The three aggregate types selected for the project were natural sand, manufactured sand, and high-fines screenings. Hopefully, these three aggregate types will be representative of a large portion of aggregates used across the country.

Guidelines for Early-Opening-to-Traffic Portland Cement Concrete for Pavement Rehabilitation indicates that it is often very difficult to adequately compact a disturbed subbase within the confines of the repair area (*6*). The principal investigator suggested that even though the high early strength CLSM material was developed primarily as a subgrade repair material, it appears to have adequate compressive strength to function as an emergency base repair. Some FHWA personnel expressed concerns about whether the material has adequate stiffness to function as an emergency base repair. Aggregate gradation and size were cited as primary factors in providing adequate stiffness. This paper focuses on the attempt to determine if partial replacement of the fine aggregate with coarse aggregate increases CLSM stiffness without compromising flow and compressive strength performance goals.

LITERATURE REVIEW

Whether the subgrade, the base, or maintenance of underground utilities is the cause, one thing is certain, the pavement must often be repaired. Subgrade and base repairs can be performed using backfill or base material that must be compacted; or a rapid-setting CLSM can be used that requires no compaction, thus saving time and money, while also improving worker safety. Repairing roadways provides users with a better product, but repairs also result in temporary lane closures that cause traffic congestion, user delays, worker safety issues, and possibly monetary penalties issued to contractors. User delays, caused by traffic congestion, are a problem that affects everyone (*7*). Roadway workers always experience some level of safety risk during repair projects. That level of risk is increased when a lane of traffic is closed, resulting in traffic congestion and a more dangerous environment. A main factor in reducing worker safety risk is to reduce the duration of repairs thus directly reducing workers time spent in a dangerous environment.

Duration of roadway repair projects also affects contractors monetarily. The Ohio Department of Transportation (ODOT) restricts projects involving high traffic roadways to nighttime hours only (*8*). Contractors are penalized $2500.00 for every 15 minute interval that a lane of traffic is closed during a time outside of the given "nighttime" hours (*8*). Other states such as Texas are implementing "Lane Rentals" in which contractors must pay a fee whenever a lane is occupied in order for work to be completed (*9*). The fees vary depending on the volume of traffic (*9*).

The Federal Highway Administration has strongly promoted operations for improving congestion for several years in the form of grants, education and outreach, technical tools, and standards development (*10*). Thus, FHWA funded the TTU CLSM project, seeing it as a great opportunity to create an innovative material that would decrease roadway repair duration, therefore lowering traffic congestion and its negative consequences. The time necessary to complete a roadway repair would be reduced due to the CLSM's quick setting characteristics that make it a faster alternative to typical compaction-requiring backfill. Costs would be reduced due to the CLSM eliminating the need for expensive compaction equipment and additional laborers. Safety risks would be lowered due to the danger of workers using compaction equipment within trenches being eliminated. Each year about 400 U.S. workers die in trenches, and 6,400 workers are seriously injured in trench cave-ins (*11*). TTU High-early strength CLSM would be one more step in making the nation's highways a safer, more user-friendly system.

The "Green" CLSM was designed with the intention of producing a high-early strength CLSM with environmentally friendly characteristics. The main step in designing a more environmentally friendly product consisted of completely replacing the portland cement content with Class C fly ash. The production of portland cement requires a tremendous amount of heat. Because of the fuel required to generate this heat, portland cement production is responsible for six to eight percent of the world's fuel consumption and is a large contributor to CO_2 emissions. The replacement cementitious material, Class C fly ash, is a byproduct of coal fired power plants. TTU "Green" CLSM would therefore have two positive impacts: making use of a byproduct that would otherwise occupy space in a landfill, and reducing portland cement production that has a negative effect on natural resources and the atmosphere.

Fly ash is commonly used in CLSM to increase flowability and to reduce segregation, permeability, and bleeding (*1*). Class C fly ash has been found to increase the strength of CLSM considerably when compared with Class F fly ash (*12*). This is mainly due to the differences in chemical composition and reactivity; similar effects occur in conventional concrete. The American Electric Power Company has introduced Flash Fill, which contains no portland cement. Flash Fill is produced by blending ASTM C 618 Class C and Class F fly ash (*13, 14*). The quick set is due to the Class C fly ash. Set times for Flash Fill range from ten minutes in hot weather to one hour in 0˚C (32^{o}F) weather (*15*). Strengths of less than 0.55-MPa (80-psi) are common at 28 days, at which strength development virtually ceases.

Landwermeyer and Rice, while studying quick-setting, excavatable CLSM mixes used in Tulsa, OK, found that the unconfined compressive strength could be tested at times of six hours or less. The quick-setting CLSM placed in the laboratory and field averaged between 0.50 and 0.57-MPa (73 and 83-psi) at 365 days, with 60 to 65 percent of this strength gained within 28 days. The regular CLSM mixes reached 4.2-MPa (615-psi) at 365 days with only 5 percent attained in 28 days in the laboratory, and 6.4-MPa (930-psi) at 180 days with 3 percent attained at 28 days for field placements (*5, 16*). A reduction of strength with age was also observed, but was determined to be a result of normal test variance (*16*). Pierce and Ihekweazu got average 24 hour unconfined compressive strengths near 0.22-MPa (32-psi) for various rapid-setting mixtures, using both chloride and non-chloride accelerating admixtures. The unconfined compressive strengths were not observed beyond 56 days for these mixtures, at which time the strengths ranged from 0.63 to 0.85-MPa (91 to 123-psi), which is still classified as excavatable. A rapid-setting non-excavatable mixture named ZOOM! developed for the Tennessee Department of Transportation hardened within six hours or less and could use three different aggregates. The mixtures containing river sand attained compressive strengths near 0.60-MPa (87-psi) at 24 hours and 2.7-MPa (392-psi) at 56 days (*17*).

The California Bearing Ratio (CBR) is a common test for relative measurement of a materials load-bearing ratio or subgrade strength (*18*). The load-bearing capacity defines the ability of a fill to support loads without failing or suffering long-term settlement (*18*). Although not commonly evaluated, the CBR is an important parameter for determining the effectiveness of the CLSM (*19*). The test method for determining the CBR of laboratory soils is ASTM D 1883 (*20, 21*). The CBR is reported as a percentage of the strength of a properly compacted crushed aggregate (CBR= 100) (*5*). Pons, Landwermeyer, and Kerns recommended a CBR value of 40 to 45 percent at 24 hours for quick-setting CLSM. The field CBR values they obtained for regular CLSM after six days were comparable to that of a poor pavement subgrade. However, these values at 45 days were comparable to an Oklahoma Department of Transportation Type A aggregate base material (*16*). For rapid-setting CLSM, the 24 hour CBR was representative of the long-term bearing strength, which can be compared to a primarily sandy or gravelly soil, which is considered a good subgrade material for pavements (*16*). Hoopes performed CBR tests on air-entrained CLSM and found that at three days the mixes achieved minimum very good subgrade category, with a CBR between 20 and 30 percent. At 7 and 56 days the CLSM achieved the good base category with CBR values between 30 and 80 percent. The data also indicated a linear relationship between CBR indexes and compressive strength (*18*).

MATERIALS

Quantities of necessary aggregates were secured and stockpiled so that the same aggregates were used throughout the laboratory evaluation. Aggregates were tested for gradation (ASTM C 136-05, ASTM C 117-04), specific gravity and absorption (ASTM C 128-04) (*20, 21, 22, 23*). Gradations are shown in tables 2 and 3. Similarly, ASTM C 618 Class C fly ash (see Table 4) and chemical admixtures (ASTM C 494) were obtained and stockpiled so that the same materials were used throughout the laboratory evaluation (*14, 16, 24*). Local tap water was used for all laboratory mixtures. Chemical admixtures (high-range water reducers and retarders) were obtained from nationally recognized suppliers.

TABLE 2 Fine Aggregate Gradations (Percent Finer by Mass)

Sieve Size (mm)	Natural Sand	Manufactured Sand	Screenings	ASTM C 33 Fine Aggregate
9.5	100	100	100	100
4.75	96	100	96	95 to 100
2.36	88	94	63	80 to 100
1.18	79	61	38	50 to 85
0.6	57	34	25	25 to 60
0.3	12	17	18	5 to 30
0.15	2	9	14	0 to 10
0.075	0.5	5.7	11	Varies

TABLE 3 Coarse Aggregate Gradation (Percent Finer by Mass)

Sieve Size (mm)	Coarse Aggregate Sample	ASTM C 33 No. 67 Stone
25.4	100	100
19.0	100	90 to 100
9.5	30.1	20 to 55
4.75	0.5	0 to 10
2.36	0.3	0 to 5

TABLE 4 Class C Fly Ash Chemical Composition

Component	Percent Composition	ASTM C 618 Requirements
SiO_2	36.51	
Al_2O_3	19.22	
Fe_2O_3	6.05	
$SiO_2 + Al_2O_3 + Fe_2O_3$	61.78	50% minimum
CaO	24.89	
MgO	6.21	
SO_3	1.34	5% maximum
Na_2O	1.60	
Loss-on-Ignition	0.15	6% maximum

RESEARCH METHODOLOGY

Preliminary Screening of Mixtures

Initial fine aggregate mixture designs were developed from experience with guidance from the literature review. Subsequently, a 0.0043-m^3 (0.15-ft^3) batch of each CLSM mixture was produced in a paddle-type, electric mixer similar to the mixer required in ASTM C 305 but larger (*25*). An ASTM D 6103 flow test was conducted on each mixture (*10*). For mixtures with a flow of 203 mm (8 inches) or more, two 100x200-mm (4x8 inch) cylindrical compressive strength cylinders were cast and tested at six hours. The mixture designs with the highest six hour compressive strength average for each fine aggregate were considered the best mixture designs and were tested further.

Intermediate Evaluation with Coarse Aggregate Substitution

A local limestone aggregate meeting ASTM C 33 No. 67 was substituted for fifty percent of the fine aggregate on an equal volume basis in the best CLSM mixture for each fine aggregate type (*26*). Flow was evaluated and the mixture design altered to produce adequate flow. The mixtures which achieved adequate flow were tested for compressive strength development. The best mixtures were tested further with larger batches as explained in the following section.

Final Evaluation of Most Promising Mixtures

Six CLSM mixtures were selected for final laboratory evaluation with a larger batch. The mixtures with adequate flow and the best compressive strengths at six hours for each fine aggregate type with and without coarse aggregate were selected. A 0.035-m^3 (1.25-ft^3) batch of each of the selected CLSM mixtures was mixed and tested as per table 5. Only the penetration phase of the California Bearing Ratio (ASTM D 1883) was performed (*27*). The static modulus of elasticity procedure (ASTM C 469) was modified with polyvinylchloride feet (see figure 1) for attaching the compressometer to the cylinder to prevent cylinder damage. The research team determined that the polyvinylchloride feet on the compressometer bolts had little effect on the static modulus of elasticity obtained by conducting side-by-side testing on identical concrete specimens at two static modulus of elasticity levels.

TABLE 5 Testing Protocol for Final Laboratory Evaluations

Test Procedure	Time of Test
Flow	Plastic state
Gravimetric Air and Unit Weight	Plastic state
Compressive Strength	4 and 6 hours, 1 and 28 days
California Bearing Ratio	6.5 and 24 hours
Static Modulus of Elasticity	28 days

CLSM FINAL MIXTURE DESIGNS

Final mixture designs are shown in tables 6 and 7. A commercially available lignosulfate retarder, ASTM C 494 Type D, was used in the mixtures in order to prevent the Class C fly ash binder from “flash setting”. Similarly, an ASTM C 494 Type F high-range water reducer was used to increase flow.

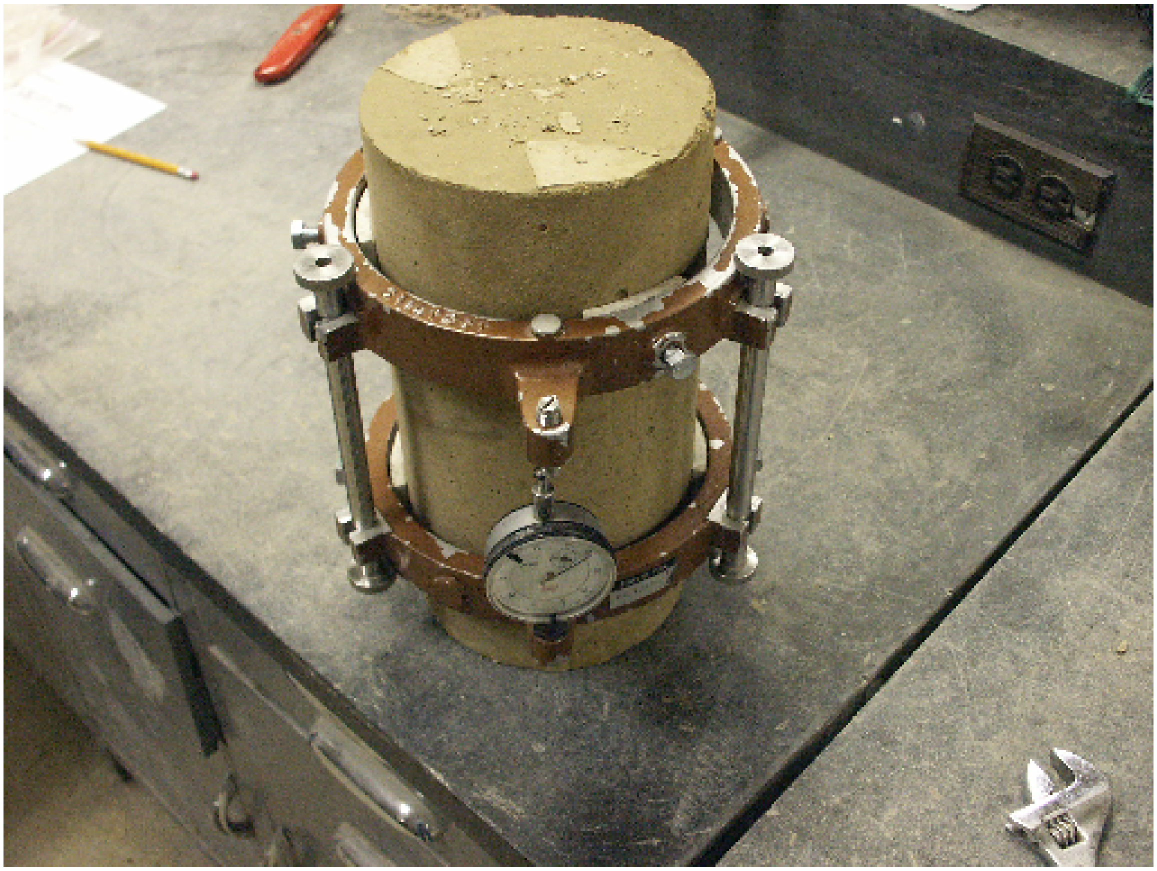

FIGURE 1 Polyvinylchloride protective feet for compressometer bolt tips.

TABLE 6 Non-air-entrained CLSM Mixtures

Component	Natural Sand	Manufactured Sand	Screenings
Class C fly ash, kg/m^3 [a]	600	650	675
Aggregate, kg/m^3	1430	1400	1376
Water, kg/m^3	216	227	230
ASTM C 494 Type D, L/100 kg [b]	0.13	0.13	0.13
ASTM C 494 Type F, L/100 kg	0.2	0.2	0.2

[a] 1 kg/m^3 = 1.6848 pcy
[b] 1 L/100 kg = 15.38 oz/cwt

TABLE 7 Non-air-entrained CLSM Mixtures with Coarse Aggregate

Component	Natural Sand	Manufactured Sand	Screenings
Class C fly ash, kg/m^3 [a]	540	650	675
No. 67 Coarse Aggregate, kg/m^3	815	751	774
Fine Aggregate, kg/m^3	780	744	771
Water, kg/m^3	189	195	168
ASTM C 494 Type D, L/100 kg [b]	0.13	0.13	0.13
ASTM C 494 Type F, L/100 kg	0	0.1	0.20

[a] 1 kg/m^3 = 1.6848 pcy

[b] 1 L/100 kg = 15.38 oz/cwt

RESULTS

Plastic and hardened property results are shown in tables 8 and 9.

TABLE 8 Engineering Properties of the Fine Aggregate CLSM Mixtures

Property	Natural Sand	Manufactured Sand	Screenings
Flow, mm [a]	400	349	273
Unit Weight, kg/m^3 [b]	2220	2141	2272
4-hour Compressive Strength, MPa [c]	0.19	0.20	0.20
6-hour Compressive Strength, MPa	0.21	0.21	0.25
24-hour Compressive Strength, MPa	2.0	2.1	1.5
28-day Compressive Strength, MPa	7.8	8.6	8.9
24-hour Static Modulus of Elasticity, GPa [d]	6.6	5.2	5.5
28-day Static Modulus of Elasticity, GPa	11.0	17.2	17.9
6.5-hour California Bearing Ratio (%)	19	19	20
24-hour California Bearing Ratio (%)	273	156	151

[a] 1 mm = 0.0394 inch

[b] 1 kg/m^3 = 0.0624 pcf

[c] 1 MPa = 145 psi

[d] 1 GPa = 145 ksi

TABLE 9 Engineering Properties of the CLSM Mixtures with Coarse Aggregate

Property	Natural Sand	Manufactured Sand	Screenings
Flow, mm [a]	254	273	222
Unit Weight, kg/m^3 [b]	2337	2343	2349
4-hour Compressive Strength, MPa [c]	0.27	0.30	0.35
6-hour Compressive Strength, MPa	0.32	0.33	0.42
24-hour Compressive Strength, MPa	3.1	2.9	4.5
28-day Compressive Strength, MPa	11.7	15.9	22.8
24-hour Static Modulus of Elasticity, GPa [d]	13.4	8.3	7.9
28-day Static Modulus of Elasticity, GPa	20.0	26.9	35.2
6.5-hour California Bearing Ratio (%)	64	55	129
24-hour California Bearing Ratio (%)	552	382	880

[a] 1 mm = 0.0394 inch
[b] 1 kg/m^3 = 0.0624 pcf
[c] 1 MPa = 145 psi
[d] 1 GPa = 145 ksi

ANALYSIS

All laboratory mixtures met the flow requirements. The average w/cm ratio for the fine aggregate mixtures and mixtures with coarse aggregate substitution was 0.35 and 0.30, respectively. Coarse aggregate substitution allowed an average 14.5 percent w/cm ratio reduction. The lower w/cm ratios reduced segregation potential and increased the reaction rate (rate of strength gain) at early ages.

All six CLSM mixtures passed the four and six hour and 28 day compressive strength goals shown in table 1. The four hour strengths ranged from 193 to 345-kPa (28 to 50-psi). The six hour compressive strengths ranged from 0.21 to 0.42-MPa (30 to 61-psi). 28-day compressive strengths ranged from 7.8 to 22.8-MPa (1125 to 3303-psi). Average compressive strengths of the mixtures with coarse aggregate substitution were 0.3 and 3.5-MPa (43 and 507-psi) at 4 and 24 hours, respectively. Figure 2 shows 1 and 28-day compressive strengths. Coarse aggregate substitution increased compressive strength by 97 percent on average at both 1 and 28 days. Several comparisons were made and trends observed when analyzing the compressive strength results obtained from laboratory testing. The first observation was the higher compressive strengths were typically obtained for mixtures with lower water-to-cementing materials ratios. The results obtained agree with theory. A higher w/cm leads to a less dense product with a more porous ITZ (Interfacial Transition Zone). The ITZ is a porous area in the paste surrounding aggregates. The ITZ is caused by one-sided growth, where cementitious products are forming next to an aggregate. ITZ is typically the “weak link” in concrete in terms of compressive strength and from the CLSM results; ITZ seems to also play an important role in CLSM compressive strength.

Static modulus of elasticity (MOE) was performed on all mixture designs at 1 and 28 days. The main purpose in testing the MOE was to determine whether the addition of coarse aggregate provided additional stiffness. Figure 3 shows 1 and 28 day modulus of elasticity results. The results confirmed the hypothesis that the addition of coarse aggregate would increase the MOE. The addition of the coarse aggregate to the CLSM mixtures increased the MOE by an average of 69 and 78 percent at 24 hours and 28 days, respectively. Further, the mixtures achieved a high level of stiffness, a minimum of 7.9-GPa (1150-ksi) at one day. Coarse aggregate substitution: increased aggregate content an average of 10.2 percent, decreased w/cm ratio an average of 14.2 percent, and as a result unit weight increased an average of 6 percent. All of these factors contributed to the increase in MOE.

California Bearing Ratio testing was performed on all mixture designs at 6.5 and 24 hours. The two main objectives of the testing were to determine whether the CLSM would be suitable for rapid base repair in addition to subgrade repair, and whether or not the CBR would increase with the partial replacement of half the fine aggregate with coarse aggregate. The answer to both of these questions was yes. Typically, a good subgrade has a CBR value of 30 percent or greater and a CBR value of 80-100 percent or greater is specified for a good base. The fine aggregate mixtures did not develop penetration resistance as fast as the mixtures with coarse aggregate substitution. However, the fine aggregate mixtures were able to reach a respectable average CBR of 19 percent at 6.5 hours and a base quality average CBR of 193 percent at 24 hours with no CBR less than 150 at 24 hours. The mixtures with coarse aggregate substitution provided more penetration resistance due to the increased stiffness provided by the coarse aggregate, increased aggregate content, lower w/cm, and higher unit weight. The mixtures with coarse aggregate substitution had average CBRs of 83 and 605 percent at 6.5 and 24 hours, respectively. No mixture with coarse aggregate substitution had a CBR less than 55 at 6.5 hours and the limestone screenings mixture had a base quality CBR of 129 percent. At 24 hours, all six mixtures were well above good base values. Coarse aggregate substitution increased CBR by 324 and 244 percent on average at 6.5 and 24 hours. CBR increased far more than compressive strength or MOE due to coarse aggregate substitution.

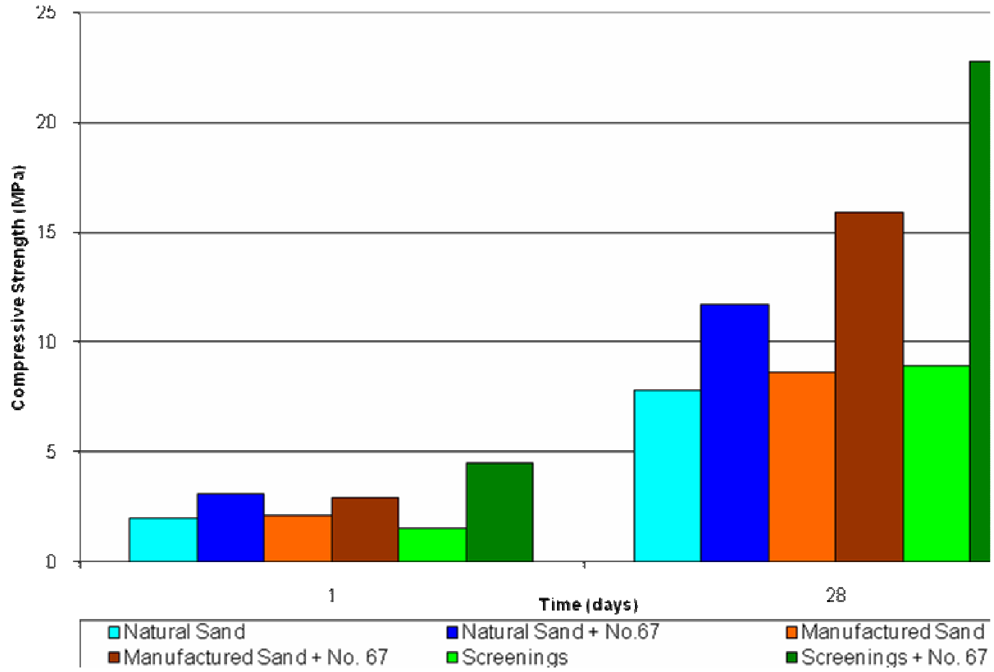

FIGURE 2 Compressive strengths at 1 and 28 days.

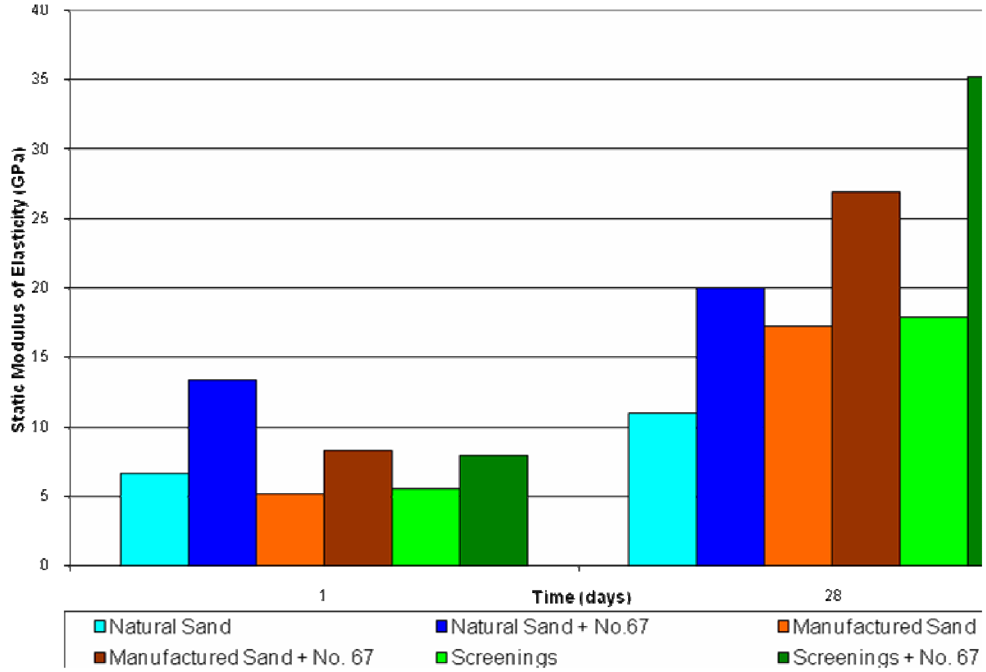

FIGURE 3 Static modulus of elasticity at 1 and 28 days.

CONCLUSIONS

The following conclusions can be drawn from the results obtained from this study:

- A high-early strength CLSM with a flow of 200-mm (8-inches) or greater and compressive strengths of 0.07-MPa (10-psi) and 0.21-MPa (30-psi) or greater at 4 and 6 hours, respectively can be achieved using a variety of commonly available aggregates and a "green" (non-portland cement) binder.
- "Green," high-early strength, CLSM mixtures containing 50 percent coarse aggregate by volume of total aggregate can be produced with adequate flow and without segregation with three different fine aggregates. The coarse aggregate substitution increased compressive strength an average of 97 percent at both 1 and 28 days. Static modulus of elasticity increased an average of 69 and 78 percent at 1 and 28 days, respectively. CBR increased by 324 and 244 percent on average at 6.5 and 24 hours.
- The "green," high-early strength, CLSM mixtures containing 50 percent coarse aggregate by volume of total aggregate achieved CBR values of an excellent base (all greater than 300) in one day. The mixtures also achieved a high level of stiffness and compressive strength, a minimum of 7.9-GPa (1150-ksi) and 2.9-MPa (426-psi), at one day.

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DISCLAIMER

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