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DEVELOPMENT OF BENDABLE CONCRETE AND RIGID PAVEMENT OVERLAY APPLICATION

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Abstract: Engineered Cementitious Composite (ECC) is a ductile fiber reinforced mortar that exhibits higher flexural capacity and significantly reduced crack width, opposed to conventional concrete. The main factor contributing to these enhancements is the polyvinyl alcohol (PVA) fibers that decrease the brittleness of conventional concrete. The mix design of the ECC proposed in previous work contains fly ash as one of its components; however, to make it relevant to Egypt, this paper replaces the fly ash with cheaper, locally produced silica fume. The experimental program includes tests to measure the compressive strength, the flexure strength, obtain stress strain curves, and measure the structural performance through dynamic loading. The outcome of these tests conveyed the enhanced ductile properties of the ECC mixes containing silica fume and fly ash as compared to conventional concrete, whereas the optimum mix was found to be the silica fume with a 25% of cement. To corroborate the results obtained, the practicality of the test was studied through an experimental model and finite element analysis. Therefore, the locally produced silica fume is more feasible to be used in the ECC mix, in Egypt. ECC shows great promise to be used in the construction industry due to its ductile nature; therefore, the paper studies the effect of using the ECC as an overlay for rigid pavements for protection and repair of rigid pavements. The ECC offers a viable alternative to asphalt overlay used in roads in Egypt due to the rising prices of petrol.

1 INTRODUCTION

Engineered Cementitious Composite (ECC) is a material which is commonly known as bendable concrete. This material exhibits some ductile behavior that resists cracking; its ductile nature could make it of important use in protection and repair of structures. This paper focuses on the application of ECC as a method of rehabilitation for rigid pavements. Rigid pavements have the shortcoming of crack formation, which is caused due to the development shrinkage cracks at the early stages whilst the concrete is setting. Shrinkage cracks occur especially in pavements that involve huge amounts of concrete due to their bulky sizes and relatively low thickness. Even in the case that cracks are not formed at the early stages of pouring the concrete, which would indicate that the shrinkage will cause stresses and will contribute to additional load effect at a later stage (Tiberti, 2018). In addition, thermal factors can have contributed to the cracking because the pavement surface is generally exposed to the atmosphere. Therefore, cracks in concrete are practically inevitable and have to be dealt with; otherwise, they would allow the penetration of water or other agents; thus, decreasing the overall durability of the rigid pavement. ECC "displays significantly higher ductility than traditional concrete and shows higher deformation ability before failure and thereby it can be used as an overlay to solve the problem of cracking" (Mavani, 2012). This is mainly obtained through its unique mix design which can be described as ductile mortar reinforced with fiber. It involves the use of polyvinyl alcohol (PVA) fibers that have a high tensile strength and modulus of elasticity. Thus, it provides a high flexural strength mix with significantly reduced crack width decreasing the brittle nature of concrete. Rather than conventional concrete, ECC does not include any coarse aggregates in the mix. It only involves the use of very fine sand as the increase in aggregate size will lead to a more difficult uniform dispersion of the fibers in the mixture. Accordingly, the aggregates size has to be less than the average fiber spacing. Other than PVA and very fine sand, ECC consists of cement, water, high range water reducer (HRWR) as a superplasticizer, and a pozzolan. Commonly, the pozzolan incorporated in the mix is fly ash that acts as a supplementary cementitious material in replacement to cement providing "similar or better fresh, mechanical and durability properties" (Mavani, 2012). However, in this paper fly ash is substituted with silica fume.

2 EXPERIMENTAL PROGRAM

2.1 Mix Design

In this paper 5 different mixes were investigated to determine the optimum mix design in terms of ductility.

Table 1: Different Mix Designs

Mix	Cement	FA/ SF	Sand	Water	HRWR	W/B*	S/B	PVA	HRWR/B
ECC-FA	1	1.2	0.79	0.57	0.012	0.26	0.36	2.00%	0.55%
ECC-SF25	1	0.25	0.45	0.4	0.012	0.32	0.36	2.00%	5%
ECC-SF29	1	0.29	0.45	0.41	0.012	0.32	0.36	2.00%	4%
ECC-SF35	1	0.35	0.45	0.43	0.012	0.32	0.36	2.00%	3%

*B is the Binder, which consists of both the Cement and the Pozzolanic Material

2.2 Mixing Process

The mixing procedure needs to be conducted prior testing. Mixing must ensure proper dispersion of the fibers and must be conducted in an adequately sized mixer. The following table shows the sequence of the activities to be mixed and their corresponding elapsed time.

Table 2: Mixing Sequence of ECC

Activity Number	Activity	Time (min)
1	Charge all the sand while mixing	1
2	Charge all the cement while mixing	1
3	Charge all the Silica Fume/ Fly Ash while mixing	3
4	Charge Silicon Oil coated PVA fibers while mixing	3
5	Charge Water+HRWR gradually while mixing	2
6	Keep mixing until reaching a homogeneous mixture	5
	Total Time	15

2.3 Compressive Strength Test

The compressive strength test was done on the cubes for each of the 4 ECC mixes as well as a control mix. Nine cubes were produced for each mix, every 3 cubes were tested at 3, 7, 28 days after pouring the mix. The mold used was 50x50 mm sized, used for mortar cubes. The test was performed using the Compressive Strength machine in order to determine the load applied. The test was conducted for various reasons; first, the compressive strength of each sample was to analyze the performance of ECC when subjected to load; the second objective was to visualize the mode of failure of the cubes after the test is performed that would convey the brittleness or rather ductility of the samples.

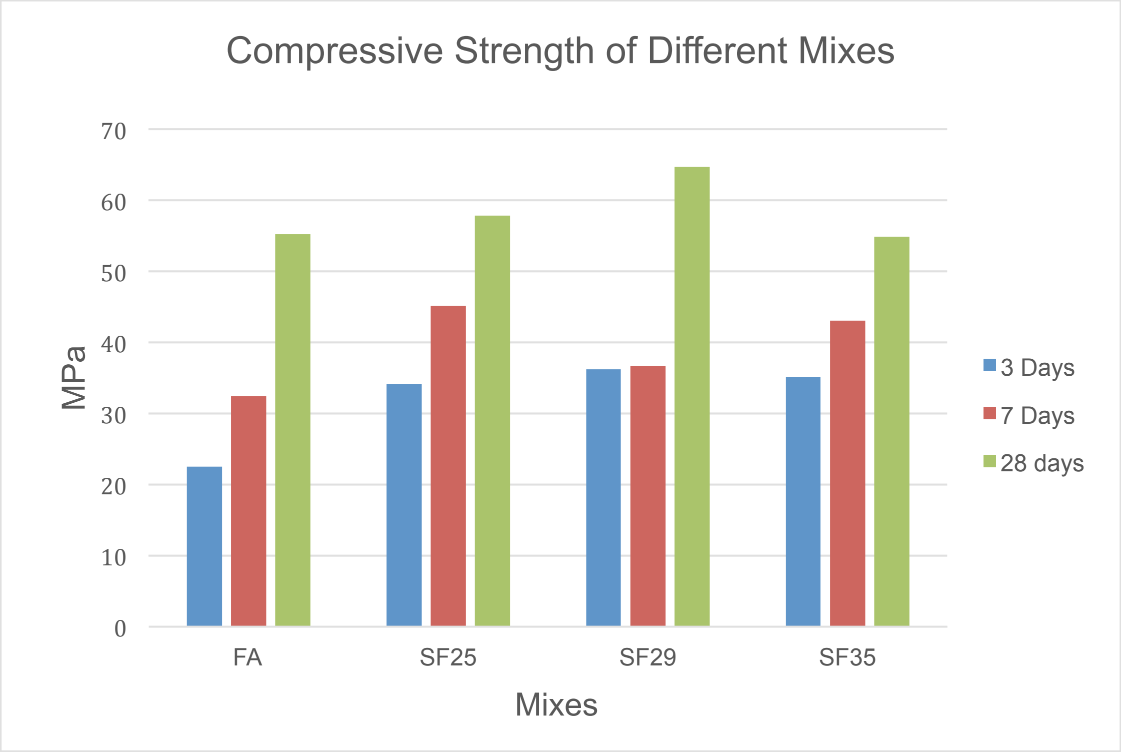

Figure 1: Summary of the Compressive test results

Table 3: Compressive Strength Results at 3, 7, and 28 days

Day	3	7	28
Sample	Stress (MPa)	Stress (MPa)	Stress (MPa)
FA	22.53	32.44	55.25
SF25	34.17	45.13	57.83
SF29	36.24	36.64	64.75
SF35	35.12	43.11	54.91
Control	21.48	35.28	54.28

2.4 Compressive Stress Strain

2.4.1 Test Design

The compressive stress strain test was done on cylinders for each of the 4 ECC mixes as well as a control mix. Nine cylinders were produced for each mix, 3 cylinders were tested at 7, 14, 28 days after pouring the mix. The samples had an average diameter of 70 mm and an average height of 120 mm. The test was conducted in order to obtain the stress strain curve of each sample and to visualize the mode of failure of the cylinders after the test is performed.

2.4.2 Test Results

The effect of the fiber in the ECC mixes showed a great difference when compared to the control mix, as ECC mixes showed high resistance to the load and the cylinders remained intact after the test was performed, unlike the control sample which showed a catastrophic failure mode. The results of this test showed that that the SF25 had the most durable form, as it had the highest stress after 28 days.

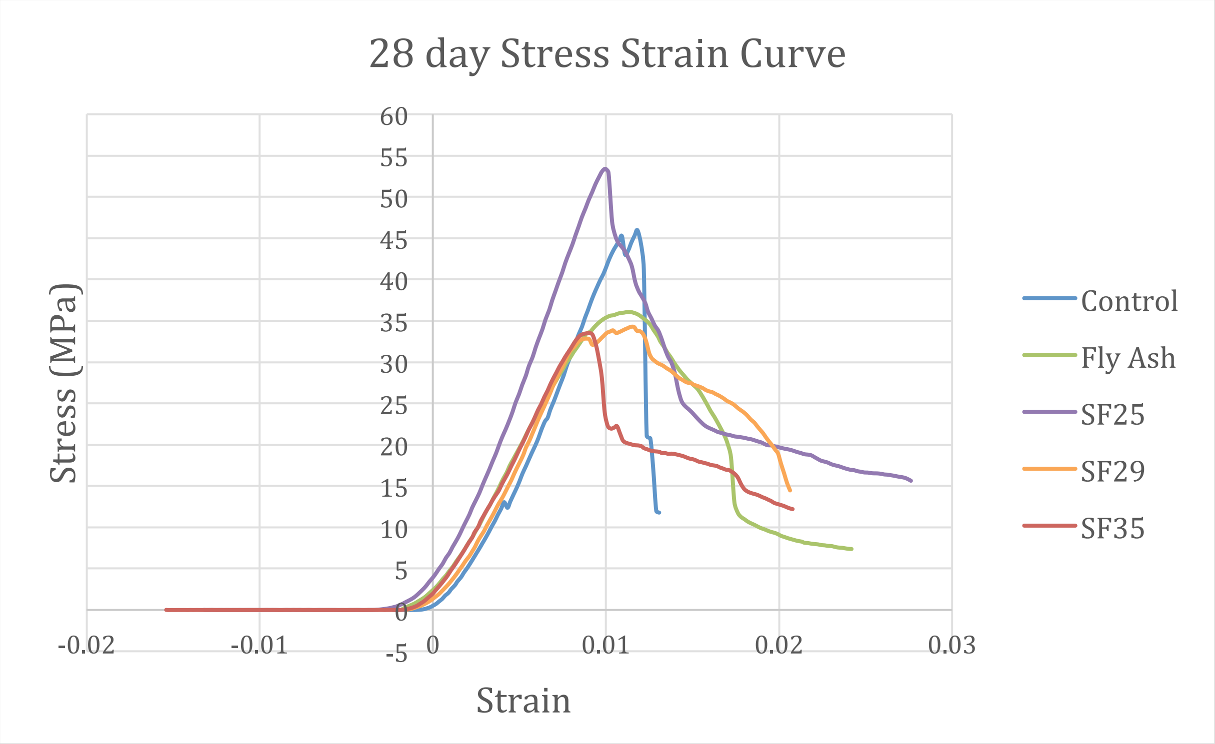

Figure 2: 28 Day Stress Strain Curves of Different Mixes

Table 4: Compressive Stress Strain Results for Mixes

Day	7		14		28	
Sample	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)
FA	23.6	0.67	30.88	1	36.06	1.14
SF25	27.89	0.72	48.67	0.94	52.5	1.04
SF29	30.8	0.91	30.8	1.04	34.24	1.16
SF35	29.14	0.97	33.78	0.8	33.88	0.92
Control	-	-	33.2	0.983	44.7	0.985

2.5 Four Point Bending Test

2.5.1 Test Design

For the 4-point load test, the used test specimen was a prism of 600 mm length, 100 mm width, and a thickness of 30 mm. The test was conducted in order to obtain the load versus deformation curve and to test the flexural capacity of the mixes. Each of the 5 mixes had 6 prisms that were poured to be tested; two prisms at 7, 14, and 28 days each. The test was performed using the MTS machine in order to determine the load applied and the corresponding deformation and to draw the load versus the deformation curve.

2.5.2 Test Setup

The test setup consisted of a base plate of 30 mm in order to have an enlarged are on the MTS machine. On top of the base plate, supports were placed in order to place the prisms on them. Loading noses were fabricated in order to be placed 150 mm apart to have an area of zero shear. The loading noses were placed on the prism and the MTS provided load and calculated the corresponding deflection. The set up was made according to the ASTM specifications (ASTM D5731 - 16).

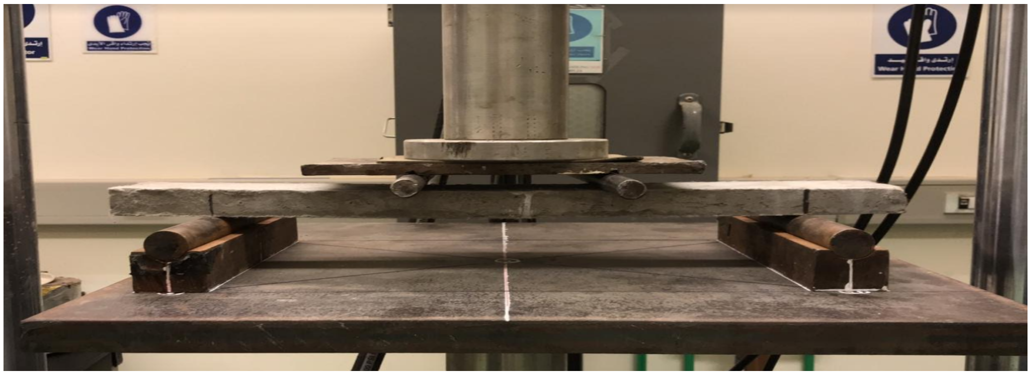

Figure 3: Four Point Bending Test Setup

2.5.3 Test Results

After the test was performed, the effect of fiber was seen using a crack microscope. The device was used to magnify the crack. Apparently, the PVA fibers action was clear as they were bridging the crack and giving the prism a more deformable shape; thus, increasing the prism’s bendability. The microscopic image below shows a crack width of 0.4mm.

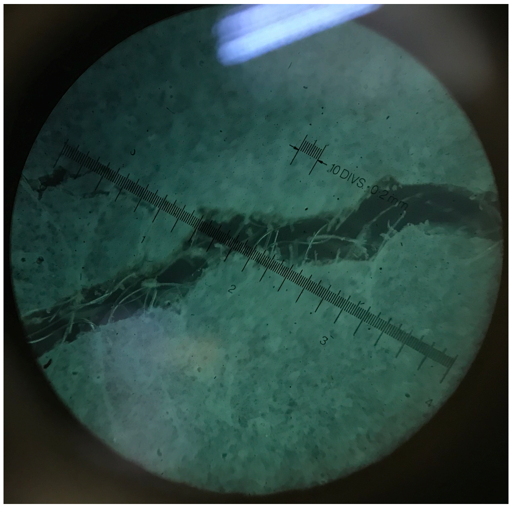

Figure 4: PVA Fiber Bridging the Crack with a scale of 10 Divisions= 0.2 mm

The loading curve showed that the Silica Fume 25% (Yellow Curve) was the best mix in the flexural test. It had the highest load and the highest deformation from the curve which is for the results at 28 days.

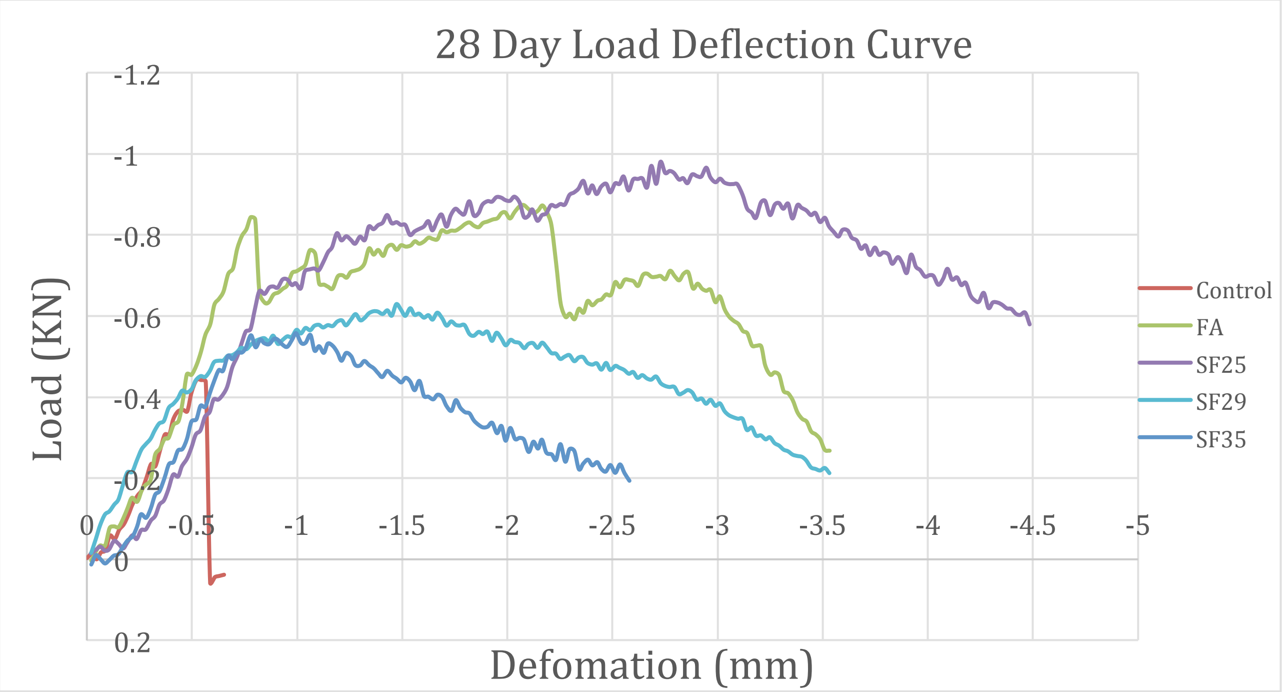

Figure 5: Flexure Results After 28 Days

2.6 Dynamic Loading Test

2.6.1 Test Design

The Dynamic loading test is set up to stimulate the load of a truck passing on a pavement through cyclic loading to reflect what happens in real life. Two samples were prepared for testing as shown in figure 3, a fully-bonded sample, where there was a complete bonding between the overlay (ECC-SF25) and the cracked concrete rigid pavement. And another unbonded sample where a small area of 150x30 mm above the simulated crack in the rigid pavement was kept unbonded, through using a plastic sheet. The preparation of the samples was initiated by placing a very thin metal divider of 2mm thickness in the middle of a steel mold (750 x 150 x 150 mm) to simulate the crack in the concrete rigid pavement. Afterwards, concrete was poured at a depth of 130 mm and left for one day to set. Finally, the 20 mm thick ECC layer is poured for the bonded and unbonded sample.

Figure 6: Sample Preparation

2.6.2 Test Setup

The test setup included a base steel plate at the bottom as shown in figure 8, and on top of it a 100 mm layer of elastic rubber which represents the base for the pavement. On top of the rubber the sample was place and tied with a reinforced-duct tape to ensure better confinement of the sample and prevent lateral movement. The samples were then ready to be tested using the "Dynamic Actuator" shown in figure 7.

Figure 7: Dynamic Actuator

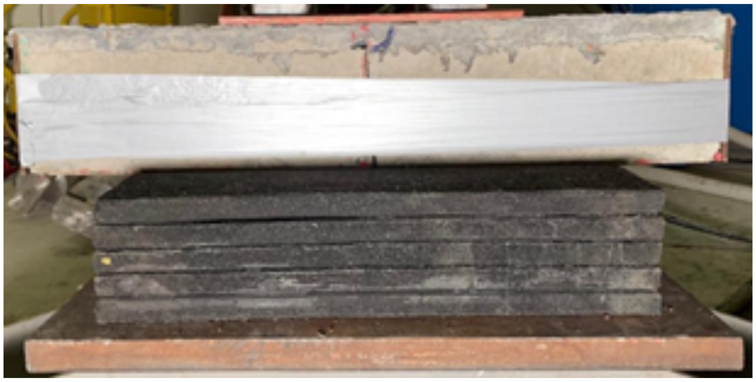

Figure 8: Dynamic Test Setup

2.6.3 Load Pattern

The cyclic load pattern used is shown in figure 8 where each cycle takes a period of one second. This one second cycle is to be divided into three phases; in the first phase a load of approximately 3.6 tons is to be applied gradually in only 0.4 seconds. Then, a gradual unloading occurs in another 0.4 seconds. Eventually, a resting period of 0.2 seconds after the unloading process. This cycle is to be repeated accordingly till observing a reflective crack propagating through the surface.

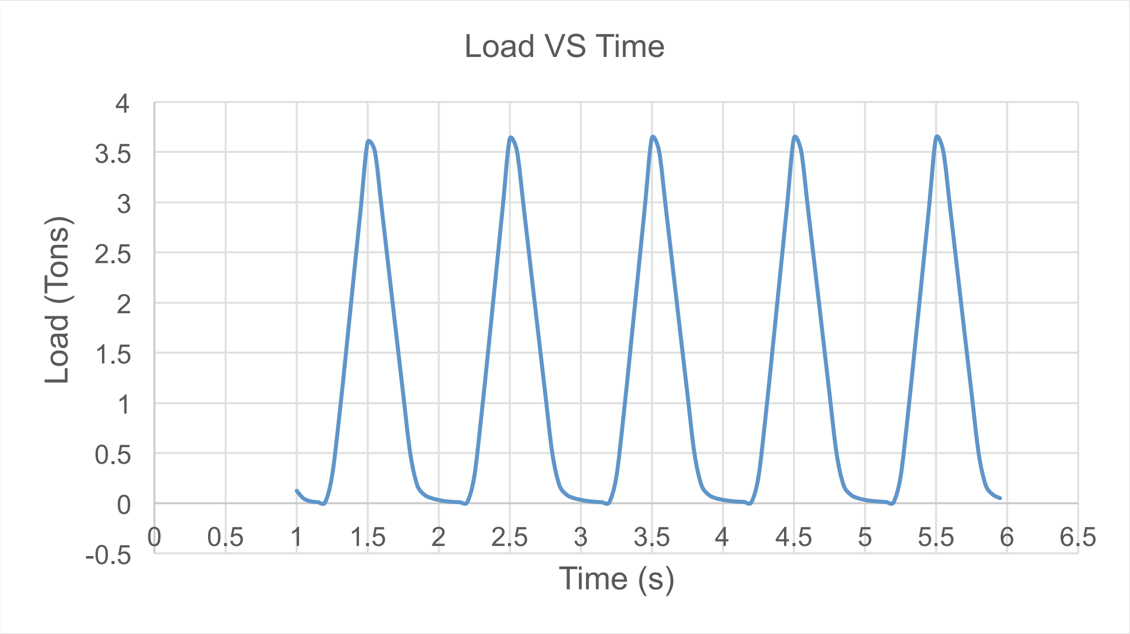

Figure 9: Dynamic/Cyclic Load Pattern

2.6.4 Test Results

The fully-bonded sample showed delamination between the layers of ECC and the concrete after only 50 cycles; in addition to a reflective crack that propagated all the way through the surface of the overlay after 230 cycles as shown in figure 8. However, the unbonded sample has shown much better results as no delamination between the layers or reflective cracks has been observed to the sample after 15,000 cycles.

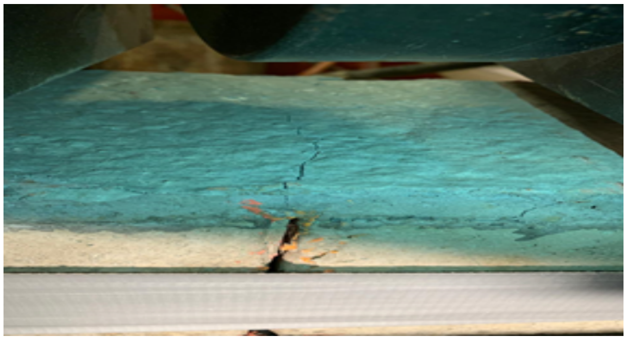

Figure 10: Bonded Sample Failure

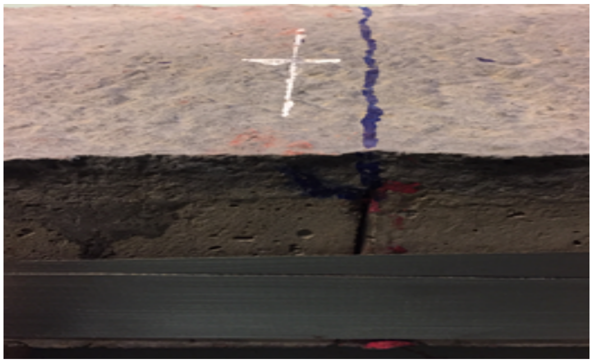

Figure 11: Unbonded Sample after 15,000 Cycles

As shown in the table 4, it was observed that the fully-bonded sample will more or less limit the flexible nature of ECC and accelerate the process of cracking on the overlay's surface.

Table 5: Dynamic Test Results

Event	Fully-Bonded Sample	Un-bonded Sample
Delamination between the layers	After 50 cycles	No delamination after 15,000 cycles
Reflective cracks	After 230 cycles	No reflective cracks after 15,000 cycles

3 NUMERICAL MODELING

3.1 Constitutive Model

The constitutive model performed on Midas GTS NX will be calibrated to the test results obtained from the dynamic test, in order to produce a numerical model that can be used in the future to analyze the effect of ECC as an overlay for large scale models. First, the 3D layer is drawn with the bottom layer represents metal plate, the layer above represents rubber, then the layer of ordinary concrete is modeled with the 2mm void in the middle that simulates a crack, finally, the ECC overlay. The next step is defining the material properties, as shown in the table below. Afterwards, the mesh is created.

Table 6: Layers, Thicknesses, Mesh Size, and Constitutive Models

Layer Name	Thickness (mm)	Mesh Size (mm)	Constitutive Model
Steel	25	25	Elastic
Rubber	100	30	Elastic
Plain Concrete	130	10	Elastic
ECC Overlay	20	10	Von-Mises

3.2 Analysis of Model

The third and final step before the analysis stage is assigning the loads and boundary conditions. The importance of assigning the boundary conditions is to simulate where the reactions would occur as well as preventing movements that did not occur in the dynamic test. The maximum load applied by the actuator in the dynamic test was almost 3.5 tons; therefore, in order to assign the load to the 3D model it should be assigned as a static pressure over the face of the ECC. Additionally, the own weight as assigned as well. Finally, the dynamic analysis of the model is conducted. First, the static load assigned previously is converted to a mass that can be analyzed dynamically. Second, a time function is added in order to define the loading pattern. Third, the analysis condition is defined as a nonlinear time dynamic analysis and the time step is set. Finally, the test is then run in order to produce results.

3.3 Results

The results obtained show a deformed shape similar to the shape obtained from the dynamic test conducted. In this constitutive, in order to determine the time or cycle when cracks will start occurring is done through the formation of plastic points. Plastic points are points at which the ECC overlay elements reach their plastic limit, indicating where a crack is likely to occur.

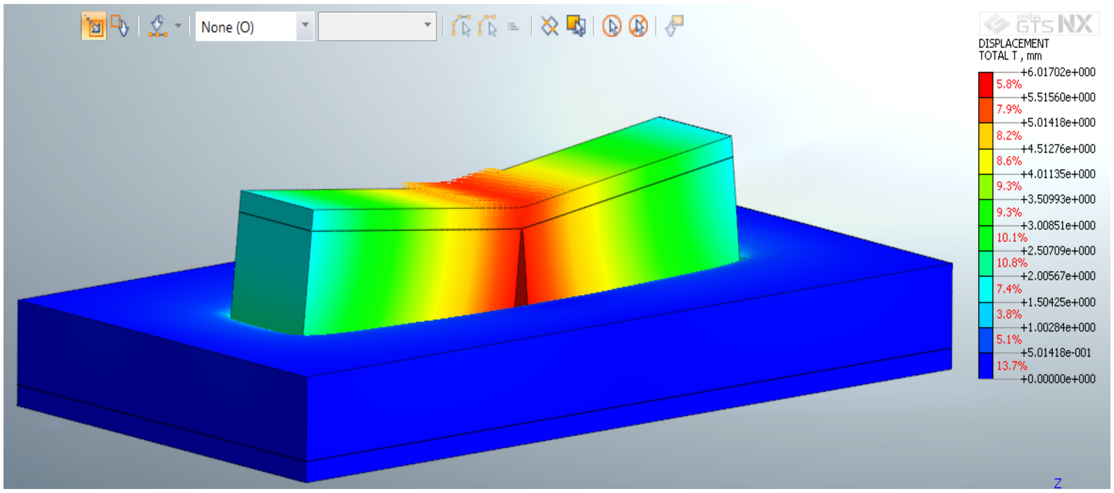

Figure 12: Deformed Shape after Running Model

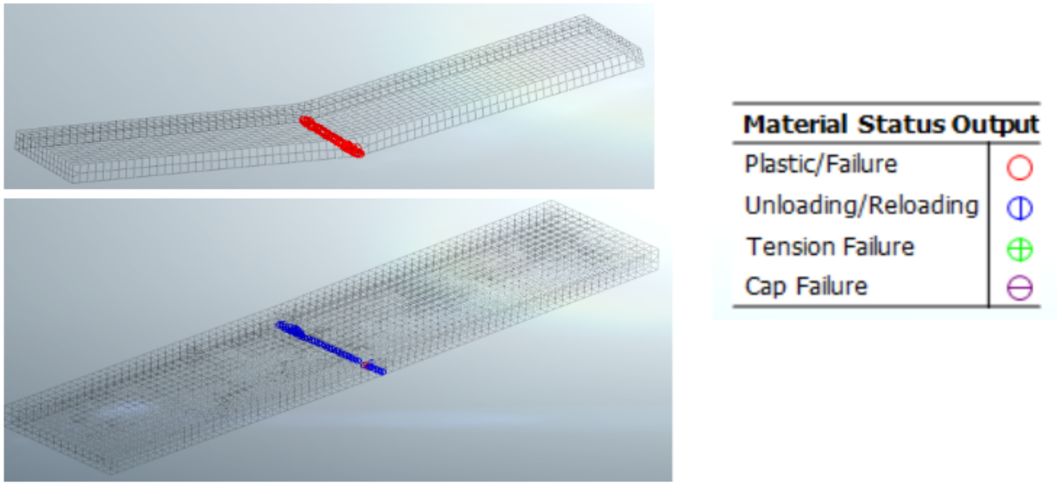

Figure 13: Plastic Points of Von-Mises Model

4 CONCLUSION

This paper examines the various mechanical properties of engineered cementitious composites of different mix designs, from which the optimum mix design is determined in order to be tested as an overlay for the rehabilitation of rigid pavements. The mixes tested were the ECC-FA, ECC-SF25, ECC-SF29, ECC-SF35, and a control mix that contained no PVA fibers. The mechanical properties determined were the compressive strength of cubes at 3, 7, and 28 days; compressive stress strain curves of cylinders at 7, 14, and 28 days; flexure capacity of prisms at 7, 14, and 28 days. It was determined that the optimum mix design is the ECC-SF25, as it has the highest flexural capacity out of all the mixes. The ECC-SF25 mix was used for the overlay for the dynamic test that was performed. The dynamic test was conducted on two samples, one fully bonded ECC-SF25 overlay, and the other being an ECC-SF25 overlay that is un-bonded over the crack. It was determined that the un-bonded ECC overlay had a far superior performance than the fully bonded overlay as it withstood more cycles without showing any delamination or cracks. Finally, a finite element analysis model was performed with a Von Mises constitutive model in order to analyze the effect of ECC as an overlay for rigid for large scale models under dynamic loading.

5 RECOMMENDATIONS

Due to the high potential that ECC has as an overlay for rigid pavements, it is recommended that it should be used; especially when the ECC overlay is un-bonded over the crack as it was determined. However, in order for ECC to be ready to be used in the market as an overlay, further tests need to be conducted in order to determine the durability of ECC, its behavior under various temperatures, porosity, resistance against chemical attack, freezing and thawing tests, and skid resistance properties of ECC. All of these tests are important to ensure that ECC is a suitable material to be used in pavements. Additionally, comparative analysis should be done between ECC and asphalt as an overlay for rigid pavements in terms of durability and cost. Finally, other uses of ECC in the construction industry should be investigated, such as its use in water tanks, its use for slab on grades for factories, and its use against impact forces.

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