Fine-grained Concrete Mix Design using Statistical Methods for Ultra-thin Whitetopping Overlay Application

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Abstract

Whitetopping is a thin layer structure covering on an existing asphalt pavement to improve resistance to rutting and increase the durability road surface. This thin layer usually made of concrete without coarse aggregate, is used mainly to repair the old damaged asphalt road surface without altering its texture. Due to the high longevity, using this type of concrete for reinforcing and repairing roads in unfavorable climatic conditions as in Vietnam brings technical, economic, environmental effective, and suitable with the trend of sustainable development. This article shows results on mix design of high performance fine - grained concrete used for thin Whitetopping overlays from materials available in Vietnam by using statistical methods. The Design Expert 11.0 software was used to evaluate the influence and relationship between the influencing variables such as the ratio Water/Binder and the Sand/Binder ratio and concrete strength through the regression equation determination by experimental planning method. After checking the compatibility, the maximum value of the compressive strength and optimum mix design were found through solving this mathematical model. The concrete with optimum proportion has good workability, high abrasion resistance; its compressive strength develops rapidly at early age and achieves more than 100MPa at 28 days. Using this Fine-grained concrete will help increasing durability and reduce the maintenance cost in the future.

Keywords: Whitetopping; Fine-grained Concrete; Compressive Strength.

1. Introduction

Overlays of Portland cement concrete on existing hot asphalt concrete pavement has been considered as a rehabilitation materials for over 80 years. These coatings have already been used in airports; Highways, main roads, even in parking lots to improve the performance, durability and quality of HMA with the deteriorated surface [1, 2]. Whitetopping has a smaller thickness with shorter joint spacing, without tie bars or joint sealing. It has a small joint spacing to minimize stress from wheel load applications as well as the humidity and temperature changes [3, 4]. If properly designed and constructed, Ultra-Thin Whitetopping (UTW) and Thin Whitetopping (TWT) can help minimize the adverse impacts associated with regular HMA pavement repairs and restoration, helping to save the annual maintenance costs [5, 6].

There are three categories of whitetopping overlays depending on the thickness and bond type between the HMA and these overlays and [7, 8]:

- Conventional whitetopping is a concrete overlay with the thichkness of 200 mm or more, designed and constructed without consideration of a bond between the concrete and underlying hot - mix asphalt.

● Thin Whitetopping is an overlay of between 100 mm and 200 mm in thickness. In most but not all cases, this overlay is designed and constructed with an intentional bond to the hot - mix asphalt.

Ultra-Thin Whitetopping - with a thickness less than 100 mm, this overlay requires a good bond to the underlying hot - mix asphalt.

The use of whitetopping was first recorded use of in the United States in 1918 [9]. There were hundreds of projects using whitetopping had been documented [10, 11]. Overall, it appears from the information gathered that the use of TWT and UTW overlays is on the increase [1, 12]. The first examples of modern UTW construction were cited in Europe and in The United States [13-15] on highways, roads or in airports because it is thinner and best suited for more lightly loaded pavements including some intersections, ramps, and light aircraft aprons. Investigation of interface treatment technique on interface shear bond fatigue behavior of Ultra-Thin Whitetopping with two interface treatment techniques like groove and piercing method have been also analyzed. The results indicated the increase in debonding leads to decrease in interface shear stress and fatigue performance [12, 16, 17].

Currently, with advanced concrete technology, the research and fabrication of thin asphalt concrete to improve the quality and durability of the pavement has been studied a lot. The concrete used for this TWT and UTW structures is usually special concrete - high strength fine grained concrete that has been successfully applied in the building industry for a few years, due to its high mechanical properties and excellent durability. Fine grain or reactive powder concrete is a high - performance concrete with high strength, high strength and low porosity [18]. Increasing the fineness and activity of the components and removing coarse aggregates to minimize internal defects of concrete (pore space and minor cracks) are the basic principles of achieving strength and strength extremely durable [19-21]. Compared with conventional concrete, the fracture strength of high - performance concrete is one step higher. Furthermore, a low Water/Binder ratio produces good pore structure and low porosity contribute to excellent durability of high - performance concrete [22-24]. In the manufacture process of whitetopping layer, the design of the concrete proportion is very important. U. Siva Rama et al., studied the Concrete Mix using Quaternary Blended Materials for Ultra-Thin Whitetopping the optimization of concrete mix design obtained by non-linear regression model had the durability and microstructure met the requirements for ultra-thin white topping concrete overlay, and suitable for making the pavement concrete mix sustainable [25]. The properties of mix concrete with varying content of polypropylene fibers and fly ash in UWT were also investigated. The results showed that compression and tensile strength increases with addition of polypropylene fibers and fly ash and can improve the compression and tensile strength, reduce the formation of cracks, plastic shrinkage, settlement and water permeability [6]. To optimize the concrete mix, many studies have used the experimental planning method. The predictive and experimental test results were very suitable because the difference between the experimental and the predicted values is less than 5%. The statistical model is significant because the difference between the predicted and adjusted R^2 is very small which indicates the significance of the statistical models. The statistical model can provide more understanding for the design of experiments and parameters that affect the concrete properties [26-28].

The overall objective of the research described in this paper was to design the mix proportions of fine-grained concrete used for ultra-thin concrete overlays as a rehabilitation option for rutted asphalt pavements. The specific objective discussed in this paper deals with using statistical methods for optimizing proportion of fine - grained concrete with good workability, high abrasion resistance; its compressive strength develops rapidly at early age and achieves more than 100 MPa at 28 days. In order to obtain the objective of the paper, it requires to determine the properties of the materials used, the theoretical basis of the experimental planning math to build the regression equation based on compressive strength. After checking the suitability of the model, the optimal concrete mix will be given to meet the requirements.

2. Materials and Experimental Methods

2.1. Materials

Materials used in this study include the ordinary Portland cement PC 40 (Vietnam) compliant the Vietnamese Standard TCVN 2682:2009 "Portland cements - Specifications", class F fly ash (FA) from Pha Lai Power (Vietnam) with activity index of 0.89, densified silica fume Elkem (SF) containing more than 92% silicon dioxide (SiO_2) with particle size in the range of $0.1-1$ μm and with activity index of 1.15; domestic river sand (S) with particle size ranging from 0.14 to 2.5 mm and specific gravity of 2.65; and superplasticizer (SP) Glenium®ACE 388 which complies with the Standard Specification for Chemical Admixtures for Concrete ASTM C494 Type G.
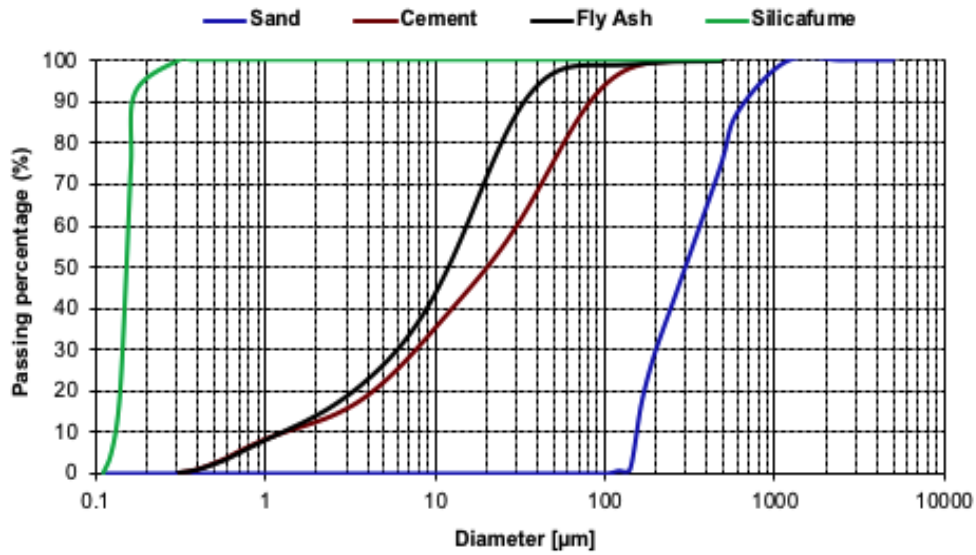
Figure 1. The grading chart of the materials

2.2. Experimental Methods

Fine-grained concrete has many important properties such as compressive strength, flowability, chloride permeability etc. However, compressive strength of concrete is used to find the optimal mix. To optimize the mix proportion of fine grained-concrete for UTW, the Response Surface Method (RSM) was used. This method consists of a set of statistical methods to develop, improve, or optimize the concrete proportion [3]. When the model of concrete was completed, the tested data sets were used to determine the accuracy of the regression to compare the predicted compressive strength with the real compressive strength.
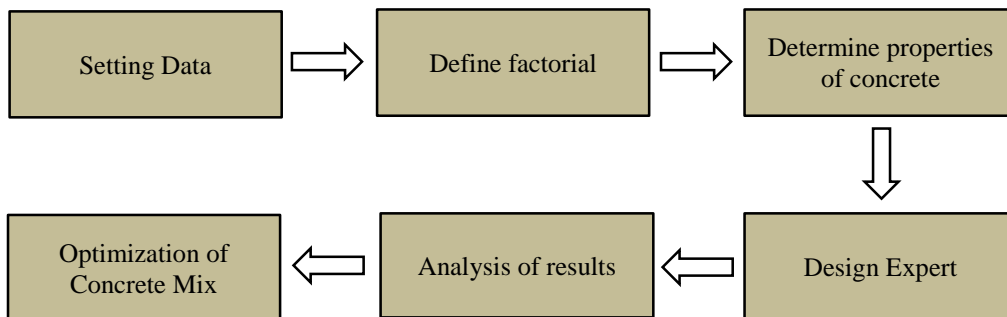
Figure 2. The research diagram

2.2.1. Mechanical Properties

After preforming the flowability tests, the fresh concrete is cast in molds with the dimensions of 50 mm × 50 mm × 50 mm. The cubes are demolded approximately 24 h after casting and then cured in water at about 25°C. After curing for 7 and 28 days, the compressive strength of the specimens is tested. At least three specimens are tested at each age to compute the average strength.

Figure 3. Samples for compressive strength of fine-grained concrete with the W/B ratio and S/B ratios

2.2.2. Flowability

To evaluate the flowability of fine-grained concrete, the flow table tests are performed following EN 1015-3. Preliminary tests demonstrated that in order to avoid segregation and bleeding, the upper limit of flow diameter was 280 mm and to achieve self-leveling behavior at fresh state the lower limit was 200 mm. Thus, flow diameter was aimed 24-26 mm and different SP dosages were used for each Water/Binder ratio.

During the test, the cone is lifted straight upwards in order to allow free flow of the mixture without any jolting. In the test, two diameters perpendicular to each other (d1 (mm) and d2 (mm)) are determined.

2.2.3. Rapid Chloride Permeability

Chloride permeability was measured in accordance with the ASTM C1202-19 Standard at the age of 28 days for optimized proportion of concrete. The 50-mm thick specimens were sliced from the top of the cylinders. The water-saturated specimens were subjected to 60-volt electric potential for 6 hours. The chloride penetration of the specimens was expressed as the total charge passed in coulomb during the test period. This is used as an indicative parameter of the chloride permeability of concrete.

2.2.4. Test Method for Abrasion Resistance of Concrete

Abrasion Resistance of Concrete (underwater Method) was measured in accordance with the ASTM C 1138 Standard. The cylindrical specimens molded (diameter 30 cm × height 10 cm) for the abrasion test, performed at 28 days of age. The apparatus used for this test consists of an electric motor, a stirring paddle, and a steel cylindrical container to hold the test specimen, to which steel balls were later added in order to provide the abrasive wear. The wear was calculated according to the mass change percentage, for 72 hours of testing, weighed prior to starting the test and 72 hours.

2.2.5. Water Permeability Resistance of Concrete

Water permeability resistance of concrete was measured in accordance with the TCVN 3116 Standard "Method for determination of water permeability resistance of concrete". This test is carried on six cylinder specimens at an age of 28 days with dimensions of 15 cm diameter × 15 cm height. The specimens are submitted to hydrostatic stress during 16h at each water pressure level. Water permeability resistance of concrete is determined by the maximum water pressure level (atm) at which four of the six specimens have not been penetrated.

3. Results and Discussion

3.1. Fine-grained Concrete Mix Design for Thin Whitetopping

The objective is to optimize mix designs for producing fine-grained concrete of high workability and high strength without bleeding and segregation. Concrete mixtures were designed based on the ACI 211.4R Guide and series of trial mixes, afterwards optimized the mix proportions to suit locally available materials as well as to achieve the highest possible level of strength. Binder of fine-grained concrete composes of cement (C), fly ash (FA) and silicafume (SF). The FA and SF are used to replace cement with silicafume to cement ratio is 10% and fly ash to cement ratio is 60%. The mixture proportion is given in Table 1:

Table 1. Basic concrete proportion

W/B	S/B	Amount of material used for 1m³ fine-grained concrete, (kg)					
		C	SF	FA	W	S	SP
0.21	1.2	571	57	343	204	1165	12.56

The optimization of the mix design was carried out following the factorial design of experiments and response surface methodology, originally developed by Box and Wilson (1951). Compressive strength at 28 days of concrete was chosen as the objective function. The main factors affecting the properties of the fresh concrete mixture are the ratio of water/binder (W/B) encoded as variable X_1, the ratio sand/binder (S/B) encoded as variable X_2.

Therefore, the quadric-order Regression model with two variable:

$$y = b_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2 + b_{11}X_1^2 + b_{22}X_2^2 + b_{112}X_1^2X_2 + b_{122}X_1X_2^2 + b_{1122}X_1^2X_2^2 \tag{1}$$

Where: y: objective function; b: the coefficients of the empirical regression equation; X_1, X_2: influencing factors are: the ratio W/B and S/B.

Number of experiments: $N = 2^n + 2n + N_0$ (2)

(N_0: Number of experiments at the center of planning experiments, with 2 variable $N_0=5$)

$N = 2^2 + 2x2 + 5 = 13$ (3)

The optimization of the mix design was realized by varying water/binder (W/B) and sand/binder (S/B). The experimental planning is presented in Table 2:

Table 2. Table of coded variables in experimental planning

Impact factors	Coded variables	Star point -1.414	Factorial point -1	Centre point 0	Factorial point +1	Star point +1.414
W/B	X_1	0.206	0.21	0.22	0.23	0.234
S/B	X_2	1.059	1.1	1.2	1.3	1.341

Based on experimental planning, the flowability of fine-grained concrete will be determined by slump flow test, D (cm). Afterward, the mixture of fine-grained concrete will be cast into moulds of 5×5×5 cm to determine the compressive strength at 28 days R_c^{28}. The matrix corresponding to the factorial design of experiments composing of the mixture proportions, the measured flowability and 28-day compressive strength of the different batches of concrete is shown in Table 3:

Table 3. Matrix of the mixture proportions, flowability and 28-day compressive strength of concrete

N°	Encoded variables		Real factors		Amount of material used for 1m³ fine-grained concrete, (kg)						Flowability, cm	Compressive strength MPa
	X_1	X_2	W/B	S/B	C	FA	SF	S	W	SP		
1	1	1	0.23	1.3	544	326	54	1201	213	12.01	29	105.9
2	-1	1	0.21	1.3	548	329	55	1211	196	12.11	23	101.8
3	1	-1	0.23	1.1	590	354	59	1103	231	13.04	29	101.3
4	-1	-1	0.21	1.1	595	357	60	1113	212	13.15	26	103.3
5	1.414	0	0.234	1.2	565	339	56	1152	225	12.48	29	108.1
6	-1.414	0	0.206	1.2	571	343	57	1166	200	12.63	12	108.1
7	0	1.414	0.22	1.341	537	322	54	1224	201	11.87	20	108.2
8	0	-1.414	0.22	1.059	603	362	60	1086	226	13.33	29	110.1
9	0	0	0.22	1.2	568	341	57	1159	212	12.56	24	111.8
10	0	0	0.22	1.2	568	341	57	1159	212	12.56	25	109.7
11	0	0	0.22	1.2	568	341	57	1159	212	12.56	25.5	110.2
12	0	0	0.22	1.2	568	341	57	1159	212	12.56	24	112.0
13	0	0	0.22	1.2	568	341	57	1159	212	12.56	25	112.4

By using software Design Expert 11.0, the regression equation of the relationship between coded variables or the real factors levels and 28 day compressive strength of fine-grained concrete were obtained as follows:

$Y = 111.22 - 0.6718 X_2 + 1.53 X_1X_2 - 1.56 X_1^2 - 1.04 X_2^2 + 1.45 X_1^2X_2 + +0.5250 X_1X_2^2 - 5.55 X_1^2X_2^2$ (4)
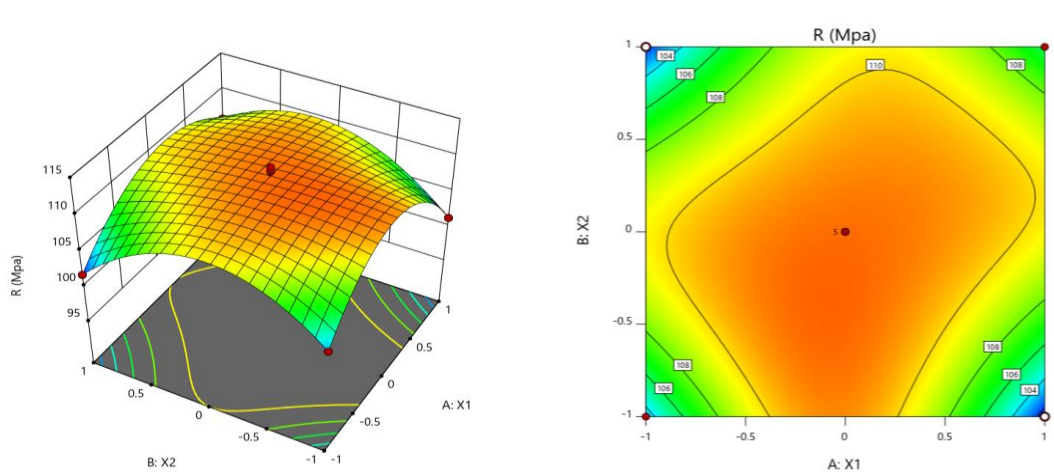

Figure 4. Three-dimensional surface and contours presenting the relationship of compressive strength of fine-grained concrete with the W/B ratio and S/B ratios

The analysis index of the regression function by Design Expert software are shown in the Tables 4 and 5:

Table 4. Sequential Model Sum of Squares of the model

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Mean vs. Total	1.514E+05	1	1.514E+05			
Linear vs. Mean	0.5726	2	0.2863	0.0167	0.9834	
2FI vs. Linear	9.30	1	9.30	0.5172	0.4903	
Quadratic vs. 2FI	89.83	2	44.92	4.36	0.0588	Suggested
Cubic vs. Quadratic	4.74	2	2.37	0.1760	0.8436	Aliased
Residual	67.29	5	13.46			
Total	1.516E+05	13	11658.94			

Table 5. ANOVA for Reduced Quartic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	*Remark*
Model	166.05	8	20.76	14.60	0.0103	significant
A-A	0.0000	1	0.0000	0.0000	1.0000	
B-B	1.80	1	1.80	1.27	0.3229	
AB	9.30	1	9.30	6.54	0.0628	
A²	13.91	1	13.91	9.78	0.0353	
B²	6.12	1	6.12	4.30	0.1067	
A²B	4.19	1	4.19	2.94	0.1613	
AB²	0.5512	1	0.5512	0.3877	0.5673	
A²B²	61.60	1	61.60	43.32	0.0028	
Pure Error	5.69	4	1.42			
Cor Total	171.74	12				

The suitability and compatibility of the R regression equation was evaluated through a number of numerical standards. This model has a high significant level of confidence becausse model F-value = 14.6 implies the model is significant. Some coefficients in the regression equation can be eliminated (Prob> F) if it is greater than 0.05 (non-significant) because the adjusted squares coefficient does not change very much the value of objective function. The results of predicted value and the experimental value are in the Figure 5 not significantly different. That proves that the regression equation given is compatible.
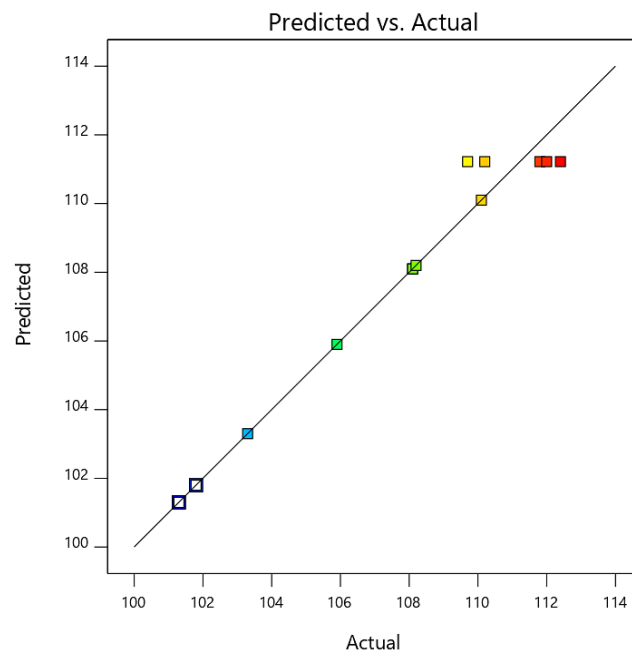

Figure 5. Correlation of predicted value and the experimental value of the model

From the regression equation, the optimal composition of fine-grained concrete was found. Afterward, the properties of fine grained concrete are investigated at the maximum value of the regression equation (4) when $X_1 = 0.051$; $X_2 = 0.027$ and the ratio W/B = 0.21; S/B = 1.203. The optimized proportion of fine-grained concrete is shown in Table 6.

Table 6. Optimized fine-grained concrete proportion

W/B	S/B	Amount of material used for 1m³ fine-grained concrete, (kg)						Flowability (cm)	Compressive strength at 28 days, R_{n28} (MPa)
		C	FA	SF	S	W	SP		
0.21	1.203	564	339	56	1154	202	12.47	26.0	113.4

3.2. Properties of high strength fine-grained concrete

To evaluate the performance of fine-grained concrete, two kinds of concrete were selected: high strength fine-grained concrete (M1) and conventional concrete of M30 grade (M2), which is widely used in road construction. Experimental results obtained are given in Table 7:

Table 7. Comparison properties of fine-grained concrete and conventional concrete

N°	Properties of concrete	Fine-grained concrete M1	Conventional concrete M2
1	Workability	Flowability (D): 26 cm	Slump number (SN): 8 cm
2	Compressive strength (MPa)		
	3 days	74.1	17.5
	7 days	91.5	25.0
	28 days	113.4	32.1
3	Flexural strength (MPa)	12.3	4.6
4	Water permeability resistance (atm)	>16	6
5	Chloride permeability (Coulombs)	330	1500
6	Water abrasion (% wt)	2.0	5.51

Experimental results show that the compressive strength at 28 days of fine-grained concrete (M1) increased 3.55 times when compared to normal concrete (M2). The flexural strength also increased by 2.67 times. That is explained by the fact that the fine-grained concrete has lower porosity by using superplasticizer and ultrafine additives which improve microstructure properties of concrete and increase the resistance of tensile and bending of concrete.

The high strength fine grained concrete designed (although containing fly ash) hardens faster than conventional concrete. The compressive strength achieved at 3 days and 7 days is a 65% and 80% respectively (compared to 28 day compressive strength), while compressive strength of the conventional concrete at 3 days is 54.5% and at 7 days is less than 78%. The water abrasion according to ASTM C1138 of fine-grained concrete also increased 2.75 times. This is one of the indicators assuring the durability of concrete designed better than conventional concrete.

The water permeability resistance of concrete M1 according to TCVN 3116 can reach the water pressure value up to 16 at; or the chloride permeability of this concrete (330 Coulombs) decreases 4.5 times when compared with the concrete sample M2 (1500 Coulombs). These are also the indicators to assess the sustainability of fine-grained concrete because the permeability are the important factors assessing corrosion durability of concrete.

4. Conclusion

From results on fine-grained concrete, some conclusions are drawn as follows:

- The statistical methods with high correlations between the compressive strength and the ratio of Sand/Binder and Water/Binder is obtained. This model can be efficiently used for simulating the compressive strength behavior and determine the optimum concrete mix design for high strength fine-grained concrete used for ultra thin white topping overlays.

- With the materials available in Vietnam, high strength fine-grained concrete can be made with compressive strength ≥100 MPa and high fowability, it can use as a thin overlayer with a thickness of 5 cm.

- Fine-grained concrete possesses a good workability. It allows the placement by means of its self-weight without any vibration or any type of compacting effort. This kind of concrete has fast strength growth at early age and

achieves high strength at 28 days. This allows speed up the construction works, especially in the road repair works and road construction.

- Resistance to abrasion of high strength fine-grained concrete is many times better than conventional conventional concrete. Therefore, this kind of concrete is suitable for the pavement layers. Bisides, fine-grained concrete using fly ash for cement replacement brings economic efficiency, helps saving energy, improving the environment and towards sustainable development.

5. Funding and Acknowledgements

6. Conflicts of Interest

The authors declare no conflict of interest.

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