*Jordan Journal of Civil Engineering,* Volume **14**, No. **2**, **2020**

# A Study on Concrete Mix with Quaternary Blended Sustainable Materials for Ultra-Thin White Topping

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## ABSTRACT

Ultra-thin white topping is a cement concrete overlay of thickness ranging between 50 mm and 100 mm over the bituminous pavement with surface failures gaining popularity in improving the long-term performance of the pavement. The use of supplementary cementitious materials (SCMs) in cement concrete pavements and overlays has high prominence in addressing the sustainability concept. In the present study, quaternary blended concrete mixes were studied for concrete overlay with a constant water-cement ratio of 0.4 to meet a minimum modulus of rupture of 4.5 MPa.The optimization of these concrete mixes for maximum modulus of rupture with minimum dosages of silica fume (S), fly ash (F) and ground granulated blast furnace slag (G) was studied using genetic algorithms. The optimal solution regarding SCM materials for the developed non-linear regression model was obtained as S = 14.72%, F = 12.82% and G = 19.29%. Further, the durability and microstructure studies were conducted on the optimized concrete mix, where it was concluded that the optimized concrete mix met the requirements for ultra-thin white topping concrete overlay improving the fresh and hardened properties of the concrete with enhanced durability and thus making the pavement concrete mix sustainable.

**KEYWORDS:** Supplementary cementitious materials, Ultra-thin white topping concrete, Ground granulated blast furnace slag (GGBS), Silica fume, Fly ash.

## INTRODUCTION

India is an emerging nation with huge construction projects widespread across the country, producing 250 million tons of cement per year. It is expected that greenhouse gas emissions would increase from 2 to 6 billion tons of carbon dioxide by the year 2030 (NBMCW, 2011). Further, the costs of projects are estimated to be higher because of more cement consumption. It's time for infrastructure engineers to think about sustainable practices which make the concrete eco-friendly, reducing the life cycle cost of concrete pavements and overlays (Anastasiou et al., 2015). The concepts of sustainability and sustainable development are receiving much attention as the causes of global warming and climatic changes are much debated. Sustainable concrete pavements, including supplementary cementitious materials as a replacement of cement, not only make pavements economic, but on the other hand improve the hardened properties of concrete, like modulus of rupture and abrasion resistance which are essential properties for long-term performance of the pavement (Bin et al., 2018). Ultra-thin white topping (UTW) is a cement concrete overlay on bituminous pavements, which was successfully executed and produced well-performing projects with different nations. UTW topping is preferred in the case of bituminous pavements structurally sound in condition with surface failures, as in the case of low-volume roads, like village roads, internal colony roads, parking lots, … etc. India has village roads which are about 80% of the total road network in length. Most of the pavements are bituminous with short-term failures, like rutting, cracking, potholes,… etc. Maintenance with a traditional bituminous overlay needs repetitive attention. UTW topping is a concrete overlay of thickness between 50 mm and 100 mm and is one of the best overlay

Received on 13/1/2019.
Accepted for Publication on 3/3/2020.

alternatives, as it provides long-term performance when compared to traditional bituminous overlay. Ultra-thin white topping concrete needs workability in terms of a slump which ranges between 35mm and 50 mm. Ultra-thin white topping concrete should meet a minimum modulus of rupture of 4.5MPa (Indian Road Congress SP-76, 2008). The key factor which affects UTW topping performance includes good bonding with the existing bituminous pavement and the use of high-performance concrete materials.

## LITERATURE REVIEW

Balbo (1999) found that the UTW overlay with 100 mm thickness at Dallas County had excellent performance. The concrete was made with fly ash as SCM material and the 28-day flexural strength was 4.7MPa (Balbo, 1999). Hall et al. (2001) reported on the UTW concrete overlay at the spirit of the Saint Louis airport, Missouri, built with class C fly ash as SCM material with polypropylene fiber and found that the flexural strength at 28 days was about 7MPa and the performance was good (Hall et al., 2001). Delatte et al. (2011) reported that high-strength concrete with fly ash or slag replacement for UTW concrete overlay improves abrasion resistance, durability and bond strength. Pereira et al. (2006) found that the UTW concrete overlay of about 100 mm thickness constructed at Sao Paulo University campus includes silica fume as SCM and the performance of the overlay was remarkably excellent. Juhasz et al. (2015) revealed that the UTW concrete overlay with 100 mm thickness at Highway Lethbridge, Alberta consists of fly ash as SCM material and synthetic fibres used in the concrete mix. Further, the investigation noted one failed panel and a handful of other panel cracks during the year. Daniel King et al. (2014) reported on the Schanck Avenue UTW concrete overlay of 100 mm thickness constructed in Chicago. The pavement is in good condition till date with the concrete mix including fly ash as SCM and synthetic fiber. Yangzhou Penga et al. (2009) studied the optimal contents for acceptable compressive strength in quaternary SCM-blended cement mortar mix, with ultra-fine fly ash, slag and silica fume reported as 10%, 17% and 15% by total weight of cement, respectively. Kumar et al. (2019) found that supplementary cementitious material (SCM) in cement concrete plays a vital role in the development of the performance of concrete. Further, the research demonstrated the importance of quaternary SCM-blended concrete in UTW overlays for bituminous roads with surface failures to improve the long-term performance of the pavement with sustainability.

### Research Significance

The literature review made clear that binary and ternary supplementary cementitious materials are used in ultra-thin white topping concrete projects and that research on quaternary supplementary cementitious material-blended concrete is very limited. The concept of sustainability induction for concrete pavements and overlays has become important across the world. Quaternary blended supplementary cementitious concrete mixes for concrete overlays help from an economic point of view, improving the fresh and hardened properties of concrete including long-term performance and reducing carbon dioxide emissions into the atmosphere, in addition to enhancing sustainability. This research paper discusses the measured fresh and hardened properties of different quaternary blended concrete mixes to meet the requirements of ultra-thin white topping concrete overlay. Further, optimization of sustainable materials for maximum modulus of rupture was carried out with the development of a nonlinear regression model using genetic algorithms. Durability microstructure studies performed on controlled and optimized quaternary blended concrete specimens support the use of sustainable materials.

## EXPERIMENTAL WORK

### *Materials*

In the present experimental investigation, ordinary Portland cement OPC of grade 53 was used. Fly ash was obtained from the Thermal Power Station, Vijayawada. Ground granulated blast furnace slag (GGBS) and silica fume were purchased respectively from Gajapati GGBS, Vishakhapatnam and Astrra chemicals, Chennai. River sand was used as a fine aggregate for all experiments. The fine aggregate was conforming to the requirements of the code IS-383 (Indian Standard 383, 1970). Specific gravity of the fine aggregate was 2.52 and the fineness modulus was found in the range of (2.3-2.6). Specific gravity of the coarse aggregate was 2.67. Water used in the UTW concrete mix design was potable, drinking water. For workability requirement of the concrete mixture, Fosroc SP430 superplasticizer was used up to a maximum of 1% by weight of cement per cubic meter.

## MIX PROPORTIONS AND METHODS

Mix proportioning of quaternary blended concrete mixes for UTW was done according to IS-10262 (Indian

Standard 10262, 2009). The concrete mix proportions adopted were 1:1.08:2.68 with a maximum cementitious content of 465 kg per cubic meter and a water-cement ratio of 0.4. To enhance the workability of the concrete mixes, Fosroc SP430 superplasticizer was added. The control concrete mix was prepared with 100% cement as cementitious material (C0). Further, in the concrete mixes from C1 to C20, half the weight of the cementitious material was replaced with combinations of silica fume, fly ash and GGBS. Mixing and curing were done as per IS-456 (Indian Standard 456, 2000). Table 1 shows the concrete mixes from C0 to C20 with the number of samples cast. Table 2 shows the concrete mix proportions for UTW concrete mixes from C0 to C20. The workability of these concrete mixes was determined by slump cone test according to IS-1199 (Indian Standard 1199, 1959). A total number of 126 concrete specimens were cast out of which 63 were of size 150 x150 x150 mm, while the remaining were of size 100 x 100 x 500 mm. These concrete specimens were cured in water for a period of 28 days. Compressive strength test was conducted as per IS-516 under a compressive testing machine of 300 tons capacity with a rate of loading of 14 N/mm$^2$/minute on concrete specimens of size 150 x 150 x 150 mm. The compressive strength is decided by taking the average of the results from three specimens and reported for each concrete mix (Indian Standard 516, 1959). Flexural strength test was conducted according to IS-516 under a universal testing machine of 100 tons capacity. The concrete beam specimens of size 100 x 100 x 500 mm were simply supported with an effective span of 400 mm and subjected to third point loading (Indian Standard 516, 1959). The average value of the results obtained from three specimens was taken as the flexural strength for each concrete mix. Table 3 shows the fresh and hardened properties for the various concrete mixes.

***Methodology for Tests Conducted on Optimized Concrete Specimens***

Durability tests were conducted on controlled concrete specimens and optimized quaternary blended concrete specimens. A total number of eight samples each with 100 mm height and 150 mm diameter were cast for conducting the Contabro and surface abrasion tests. The Contabro abrasion test was conducted without placing the abrasive charge in the Los Angeles abrasion testing machine in accordance with ASTM C1747/C1747M-11 (American Society for Testing and Materials C1747/C1747M-11, 2011). In this test, cylindrical specimens of 150 mm diameter and 100 mm height were placed in the Los Angeles abrasion testing machine. The initial weight of each specimen was recorded before placing it into the machine. Then, the machine was allowed to rotate at 300 rpm. The final weight of the specimen is noted down. The average weight loss of the two specimens was recorded.

The surface abrasion resistance test was conducted on a drill press with a rotating cutter in accordance with code ASTM C 944/C944M-12 (American Society for Testing and Materials C 944/C944M-12, 2011). In this test, two cylindrical specimens of size 150 x 100 mm were used to measure the weight loss in percentage. The initial weight of each cylindrical specimen was noted down as W1. Each of the specimens was placed in the drill press and the rotating cutter was mounted slowly until it touched the surface of the specimen. Then, the device was set to rotate for six minutes at a speed of 200 rpm with a vertical load of 98 N. The total diameter of the rotating cutter was 82.50 mm. Then, the specimen was removed from the device and its surface was cleaned and weighed (W2) to the nearest 0.1 g. The average weight loss of the two specimens in percentage was recorded.

**Table 1. Concrete mixes with number of samples cast**

| Concrete Mix Proportions | Mix | No. of samples |
|---|---|---|
| 100%C | C0 | 6 |
| 50%C+30%F+10%S+10%G | C1 | 6 |
| 50%C+10%F+30%S+10%G | C2 | 6 |
| 50%C+10%F+10%S+30%G | C3 | 6 |
| 50%C+25%F+15%S+10%G | C4 | 6 |
| 50%C+15%F+25%S+10%G | C5 | 6 |
| 50%C+10%F+15%S+25%G | C6 | 6 |
| 50%C+25%F+10%S+15%G | C7 | 6 |
| 50%C+15%F+10%S+25%G | C8 | 6 |
| 50%C+10%F+25%S+15%G | C9 | 6 |
| 50%C+20%F+15%S+15%G | C10 | 6 |
| 50%C+15%F+20%S+15%G | C11 | 6 |
| 50%C+15%F+15%S+20%G | C12 | 6 |
| 50%C+20%F+20%S+10%G | C13 | 6 |
| 50%C+20%F+10%S+20%G | C14 | 6 |
| 50%C+10%F+20%S+20%G | C15 | 6 |
| 50%C+30%F+15%S+5%G | C16 | 6 |
| 50%C+15%F+30%S+5%G | C17 | 6 |
| 50%C+5%F+30%S+15%G | C18 | 6 |
| 50%C+5%F+15%S+30%G | C19 | 6 |
| 50%C+30%F+5%S+15%G | C20 | 6 |

*** F-Fly ash, S-Silica fume, G-GGBS, C-Cement, Fine agg-Fine aggregate, Coarse agg-Coarse aggregate.**

Further microstructure studies were conducted on control concrete and optimized quaternary blended concrete samples. The methodology adopted is discussed below. The concrete samples for these studies were taken as a fine powder from hardened concrete with a little quantity of about 30 gms.

The X-Ray diffraction method was used to understand the structure of the minerals and know their properties. XRD was performed on a diffractometer by employing Cu-Kα radiation in the range of 2 theta=10° to 70° maintained at 40 kV and 15mA to detect the different mineral phases. The diffraction data provided by the International Center for Diffraction Data was used to identify clearly the mineralogical phases as present in the concrete mixes prepared from ordinary Portland cement and other supplementary cementitious materials (International Centre for Diffraction Data, 1978).

Scanning Electron Microscope (SEM) method was used to study the morphological characteristics of the concrete mix prepared from OPC, fly ash, silica fume and GGBS. The test was conducted as per the standard procedure established. The Energy Dispersive X-Ray method is an analytical technique to characterize sustainable concrete materials.

### *Formation of Statistical Regression Model*

The average modulus of rupture test results obtained for different concrete mix specimens with supplementary cementitious material dosages was used for the formation of the statistical non-linear regression model. The "damped least squares" method, an iterative technique, was used in the context of fitting the parameter objective function to a set of data points by minimizing the least square error between the data points and the function. The statistical nonlinear regression model developed with the modulus of rupture as the objective function with three independent variables (fly ash, silica fume and GGBS) has an $R^2$ value of 89%, which shows the goodness of fit. Figure 1 shows the goodness of fit characteristics for the non-linear regression model developed. Figure 2 shows the modulus of rupture measured and computed from the model. The following statistical nonlinear regression model shows the best fit for modulus of rupture of the concrete mixes with sustainable materials as independent variables with a fixed cementitious content of 465 kg per cubic meter and a water-cement ratio of 0.4, as shown in Eq. (1).

### *Validation of Non-linear Regression Model Developed*

The validation of statistical non-linear regression model developed was carried out with the similar experimental work done by Niragi et al. (2017). It was concluded that the modulus of rupture variation has a similar trend line with the variation of dosages of silica fume, fly ash and GGBS in quaternary blended concrete mixes. Table 4 shows a comparison of the modulus of rupture obtained from previous research and that obtained from the model developed.

### *Optimization Using Genetic Algorithms*

Genetic algorithms are easy to construct and deploy Darwin's theory "the survival of the fittest", which requires less storage space with a little time frame. A variety of linear and nonlinear problems can be easily solved by this technique. This optimization technique is based on the principle of biological evolution and is one of the best of its kind. The developed non-linear regression model was subjected to the following conditions: a) sum of the dosages of the three supplementary cementitious materials in a concrete mix should be less than 50% b) dosage of each supplementary cementitious material in the concrete mix should be less than 30% and c) minimum modulus of rupture of the concrete with various supplementary cementitious materials should be 4.5 MPa. The optimal solution regarding sustainable materials (silica fume, fly ash and GGBS) obtained was respectively 14.72%, 12.82% and 19.29% with the objective function modulus of rupture value as 6.34 MPa.

## RESULTS AND DISCUSSION

### *Fresh and Hardened Test Results*

The tests conducted on the fresh properties of blended concrete mixes show that workability is good for all the concrete mixes and the slump value obtained was between 100 mm and 150 mm. Concrete mixes with fly ash dosage up to 30% along with a combination of silica fume and GGBS enhanced the workable nature due to less specific surface area. Concrete mixes with silica fume dosage above 20% along with a combination of fly ash and GGBS made sticky concrete mixes, reducing workability. Even concrete mixes with GGBS dosage up to 30% along with fly ash and silica fume combination have less workability, which can be observed in the case of C4 and C19.

The quaternary supplementary cementitious material blended concrete specimens with fly ash dosage up to 30% along with a combination of silica fume and GGBS corresponding to C1, C6, C10, C12 and C19 were observed to produce higher compressive strength at 28 days. Similar results were obtained in the case of concrete specimens with GGBS dosage up to 30% in combination with fly ash and silica fume. These concrete mixes with a better combination of supplementary cementitious materials contributed to a better pozzolanic reaction and yielded enhanced strength. Concrete specimens with silica fume dosage up to 20% along with a combination of fly ash and GGBS were observed to have relatively less compressive strength, as the concrete mix was less workable and had difficulties in compaction.

The concrete specimens corresponding to mixes C1, C10, C11, C12 and C19 were observed to have higher modulus of rupture competing with control concrete specimens having an average modulus of rupture of 6.5 MPa. The quaternary blended concrete specimens with sustainable material replacements of about 15%-20% were observed to produce better modulus of rupture.

Further, the confirmatory flexural strength test was conducted on optimized quaternary blended concrete specimens with size 100 mm x100 mm x500 mm, where it was found that the average result from three specimens as 6.2 Mpa matched with the objective function modulus of rupture obtained from optimization technique adopted.

***Durability Tests Results***

Contabro abrasion test was conducted and it was observed that the weight loss of the control and optimized quaternary SCM blended concrete specimens is 8.55% and 12.0%, respectively.

Surface abrasion test was conducted, it was observed that both control and optimized quaternary SCM blended concrete specimens have the same abrasion resistance. The results show that the weight loss of the control and optimized quaternary blended concrete specimens is 0.3% and 0.29%, respectively.

$$Mr\left(28\ days\right) = 7.8 + 780\ SFG - 307\ S^2F - 467\ S^2G - 123\ SF^2 + 157\ SG^2 \\ - 243\ F^2G - 262\ SG + 103\ S^3 + 39\ F^3 - 54\ G^3 \qquad (1)$$

**Table 2. Proportions for quaternary blended concrete mixes**

| Mix | Cement | Fly ash | Silica fume | GGBS | Water | SP | Fine agg. | Coarse agg. |
|---|---|---|---|---|---|---|---|---|
| C0 | 465 | 0 | 0 | 0 | 186 | 0 | 502 | 1246 |
| C1 | 232.5 | 139.5 | 46.5 | 46.5 | 186 | 4.65 | 502 | 1246 |
| C2 | 232.5 | 46.5 | 139.5 | 46.5 | 186 | 4.65 | 502 | 1246 |
| C3 | 232.5 | 46.5 | 46.5 | 139.5 | 186 | 4.65 | 502 | 1246 |
| C4 | 232.5 | 116.25 | 69.75 | 46.5 | 186 | 4.65 | 502 | 1246 |
| C5 | 232.5 | 69.75 | 116.3 | 46.5 | 186 | 4.65 | 502 | 1246 |
| C6 | 232.5 | 46.5 | 69.5 | 116.3 | 186 | 4.65 | 502 | 1246 |
| C7 | 232.5 | 116.25 | 46.5 | 69.75 | 186 | 4.65 | 502 | 1246 |
| C8 | 232.5 | 69.75 | 46.5 | 116.3 | 186 | 4.65 | 502 | 1246 |
| C9 | 232.5 | 46.5 | 116.3 | 69.75 | 186 | 4.65 | 502 | 1246 |
| C10 | 232.5 | 93 | 69.75 | 69.75 | 186 | 4.65 | 502 | 1246 |
| C11 | 232.5 | 69.75 | 93 | 69.75 | 186 | 4.65 | 502 | 1246 |
| C12 | 232.5 | 69.75 | 69.75 | 93 | 186 | 4.65 | 502 | 1246 |
| C13 | 232.5 | 93 | 93 | 46.5 | 186 | 4.65 | 502 | 1246 |
| C14 | 232.5 | 93 | 46.5 | 93 | 186 | 4.65 | 502 | 1246 |
| C15 | 232.5 | 46.5 | 93 | 93 | 186 | 4.65 | 502 | 1246 |
| C16 | 232.5 | 139.5 | 69.5 | 23.25 | 186 | 4.65 | 502 | 1246 |
| C17 | 232.5 | 69.5 | 139.5 | 23.25 | 186 | 4.65 | 502 | 1246 |
| C18 | 232.5 | 23.25 | 139.5 | 69.5 | 186 | 4.65 | 502 | 1246 |
| C19 | 232.5 | 23.25 | 69.5 | 139.5 | 186 | 4.65 | 502 | 1246 |
| C20 | 232.5 | 139.5 | 23.25 | 69.5 | 186 | 4.65 | 502 | 1246 |

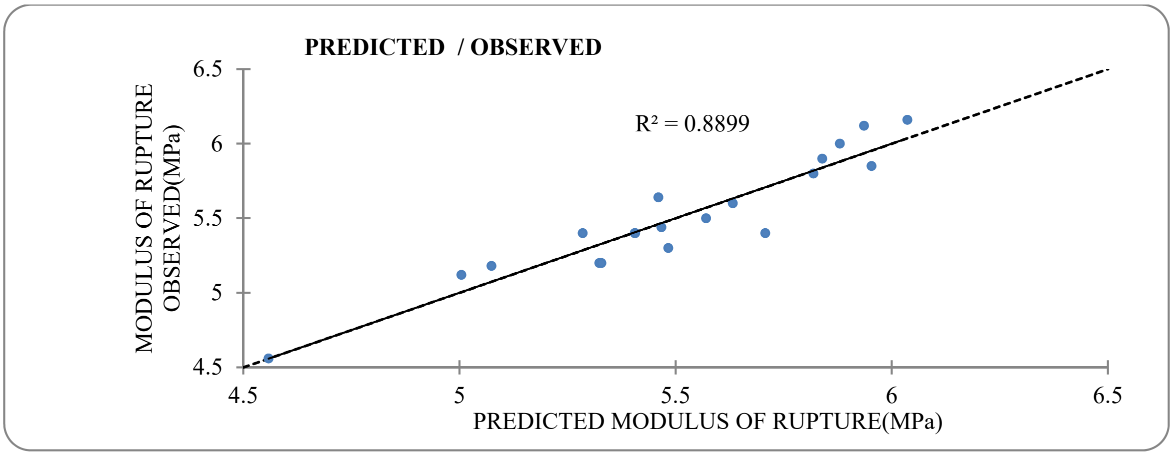


**Figure (1): Goodness of fit for the non-linear regression model**

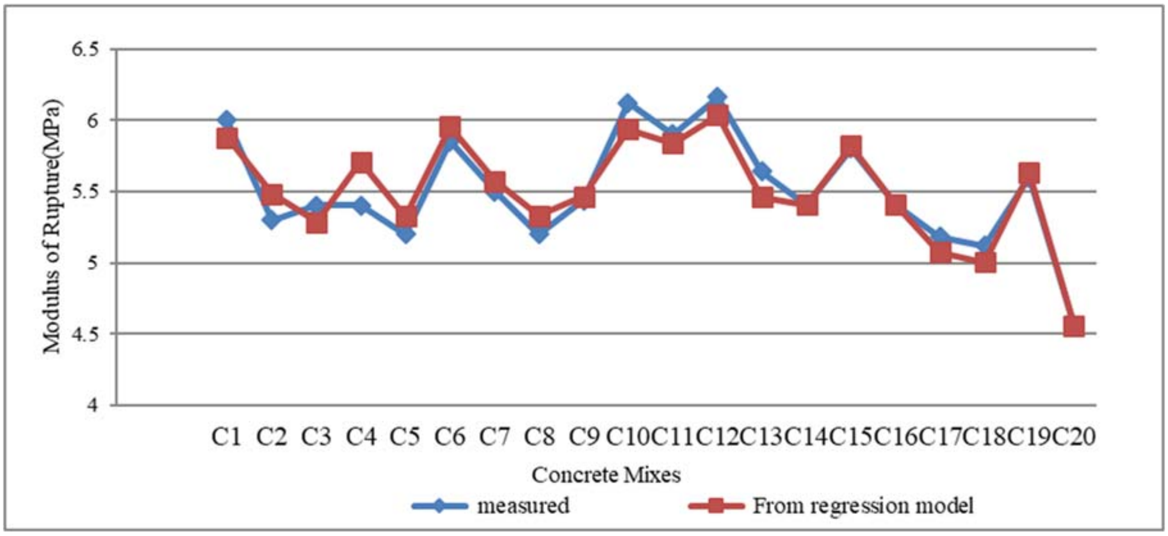


**Figure (2): Modulus of rupture measured and computed from the model**

**Table 3. Workability and mechanical properties of fresh and hardened concrete**

| Mix No. | Slump in mm | 28-day modulus of rupture (MPa) | 28-day compressive strength (MPa) | Predicted modulus of rupture from the model | 28-day MR/Predicted MR |
|---|---|---|---|---|---|
| C0 | 110 | 6.5 | 52 | NIL | NIL |
| C1 | 130 | 6 | 56 | 5.880 | 1.02 |
| C2 | 130 | 5.3 | 44 | 5.483 | 0.97 |
| C3 | 100 | 5.4 | 48 | 5.285 | 1.02 |
| C4 | 120 | 5.4 | 48 | 5.707 | 0.95 |
| C5 | 125 | 5.2 | 42 | 5.324 | 0.98 |
| C6 | 100 | 5.85 | 54 | 5.953 | 0.98 |
| C7 | 100 | 5.5 | 49 | 5.571 | 0.99 |
| C8 | 100 | 5.2 | 41 | 5.328 | 0.98 |
| C9 | 95 | 5.44 | 46 | 5.467 | 1.00 |
| C10 | 125 | 6.12 | 56 | 5.936 | 1.03 |
| C11 | 120 | 5.9 | 52 | 5.839 | 1.01 |
| C12 | 100 | 6.16 | 57 | 6.036 | 1.02 |
| C13 | 100 | 5.64 | 48 | 5.460 | 1.03 |
| C14 | 150 | 5.4 | 47 | 5.405 | 1.00 |
| C15 | 135 | 5.8 | 54 | 5.819 | 1.00 |
| C16 | 150 | 5.4 | 45 | 5.407 | 1.00 |
| C17 | 120 | 5.18 | 42 | 5.074 | 1.02 |
| C18 | 150 | 5.12 | 41 | 5.005 | 1.02 |
| C19 | 100 | 5.6 | 52 | 5.632 | 0.99 |
| C20 | 130 | 4.56 | 40 | 4.558 | 1.00 |

**Table 4. Comparison of modulus of rupture obtained from previous research and the model developed**

| Mix | Concrete Mix proportion | Niragi (MR value in MPa) | Our model (MR value in MPa) | Concrete Mix code |
|---|---|---|---|---|
| 1 | 50%C+10%F+30%S+10%G | 8.3 | 7.4 | C2 |
| 2 | 50%C+20%F+15%S+15%G | 7.9 | 6.6 | C10 |
| 3 | 50%C+20%F+15%S+15%G | 7 | 5.4 | C11 |

**Table 5. Contabro and surface abrasion test results**

| S. No. | Description | Contabro abrasion test | Surface abrasion test |
|---|---|---|---|
| | | Weight Loss (%) | |
| 1 | Control Samples | 8.55 | 0.3 |
| 2 | Optimized quaternary blended samples' weight loss (%) | 12 | 0.29 |

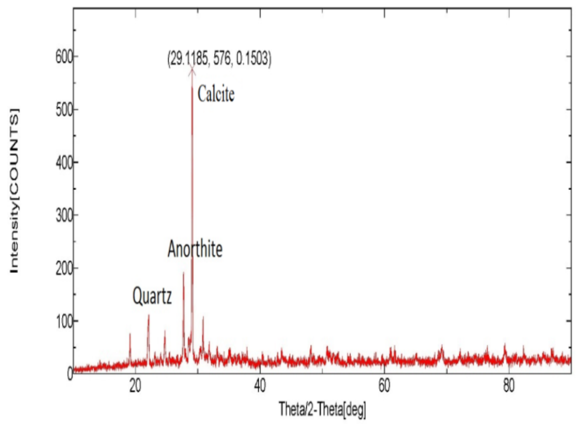


**Figure (3): X-ray diffraction pattern of the control sample**

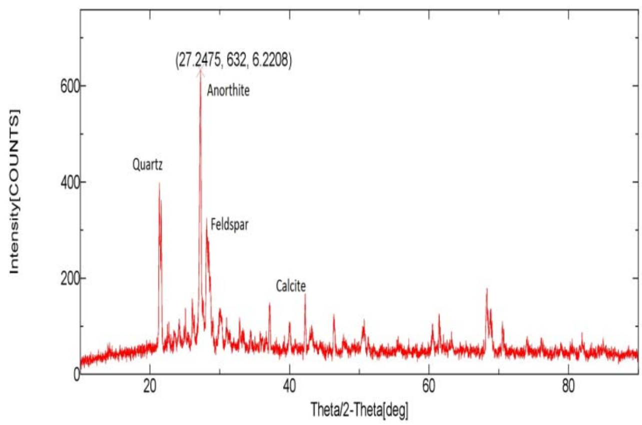


**Figure (4): X-ray diffraction pattern of optimized quaternary blended concrete mix**

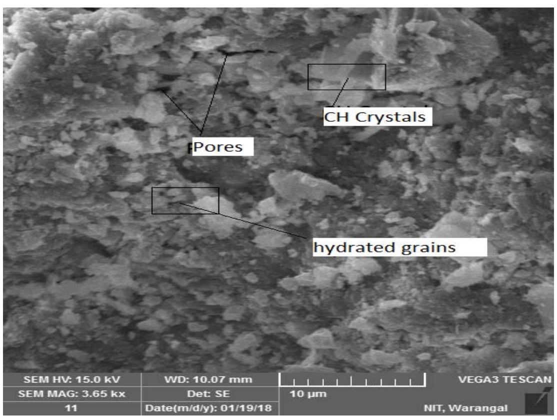


**Figure (5): SEM image of cement hydration for the concrete control sample**

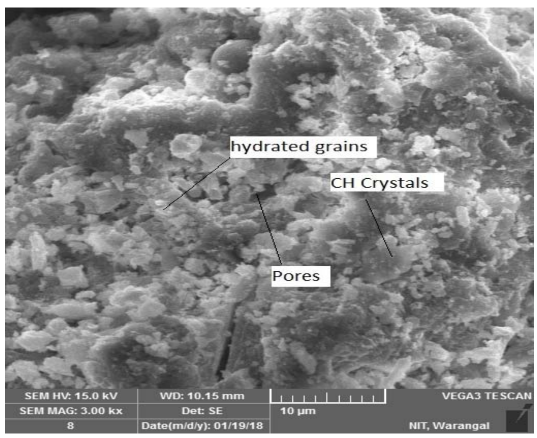


**Figure (6): SEM image of cement hydration for optimized quatenary blended SCM mix**

***Microstructure Studies and Results***

In the case of concrete control samples, XRD diffraction patterns exhibited the presence of a majority of crystalline phases of calcite, quartz and calcium aluminum silicate (anorthite). The other peaks correspond to the hydration process formation minerals, such as C-S-H and C-A-S-H.

In the case of optimized quaternary blended concrete samples, XRD diffraction patterns exhibited the presence of the majority of mineral anorthite. It was clearly observed that peaks of calcite are reduced and calcium aluminum silicate mineral improvement was made with the replacement of SCM materials. The abundance of the presence of mineral anorthite confirms the higher modulus of rupture in the case of an optimized quaternary blended concrete mix.

Scanning Electron Microscope (SEM) has become an important tool in the investigation of the microstructure of concrete, essentially the hydrated cement paste structure.

In the case of the concrete control sample, the formation of cementitious compounds in the form of hydrated grains was clear from the microstructure. In the ordinary Portland cement concrete, the calcium silicate present reacts with water to form (1) crystalline calcium hydroxide (CH) which appears in different shapes and sizes and (2) calcium silicate hydrate (C-S-H) gel which is the most important component in the development of necessary binding property and helps improve the strength of concrete.

In the case of optimized quaternary blended concrete samples, the formation of cementitious compounds in the form of C-S-H gel appears to be denser with fewer pores when compared with the control samples. The addition of silica fume, fly ash and GGBS along with cement made the C-S-H gel denser, which was clear from the microstructure. Further CH crystals formed are reduced in this concrete with the addition of mineral admixtures enhanced to refine the aggregate and paste interface.

Dispersive X-ray analysis conducted on concrete control samples showed that C-S-H gel has a composition of minerals with a Ca/Si ratio of about 3.2. Further, in the analysis of optimized quaternary blended concrete samples, it was seen that C-S-H gel has the composition of minerals with a lower Ca/Si ratio of about 1.5 when compared with the concrete control mix. The concrete having less Ca/Si ratio in the C-S-H gel contributes to better mechanical properties with good elastic modulus and hardness (Fernando Pelissier et al., 2012).

## CONCLUSIONS

Conclusions drawn from the experimental analysis of quaternary blended concrete mixes and optimized concrete mixes for ultra-thin white topping concrete overlays are as follows:

1. The statistical non-linear regression model developed between modulus of rupture and independent variables of supplementary cementitious materials has shown goodness of fit with an $R^2$ value of 89%. Further, the modulus of rupture variation with various dosages of different supplementary cementitious materials computed from the model agreed with similar trend line by the research conducted by Niragi et al. on quaternary blended concrete mixes.
2. The optimized dosages of supplementary cementitious materials silica fume (S), fly ash (F) and GGBS (G) are obtained as 14.72%, 12.82% and 19.29% with the objective function maximum modulus of rupture value of 6.4 MPa. These optimum dosages obtained are in agreement with a previous research conducted by Yangzhou Penga et al. in terms of that maximum packing density for the quaternary blended cement mortar mix needs dosages of silica fume, fly ash and GGBS as respectively 15%, 10% and 17% by total weight of cementitious material consumption. Moreover, the obtained modulus of rupture was greater than the minimum value of 4.5 MPa for UTW concrete overlay and hence met the requirements.
3. Contabro abrasion test and surface abrasion test conducted on optimized quaternary sustainable material blended concrete control specimens and concrete specimens showed that weight loss percentage difference between both tests is not much. From this, we can say that optimized quaternary blended concrete specimens are abrasion-resistant competing with concrete control specimens and hence helping improve the long-term performance of the concrete overlay.
4. The microstructure studies conducted on the optimized quaternary blended concrete samples showed a clear indication of the formation of C-S-H gel with densification and less Ca/Si ratio when compared with the concrete control samples, which helped enhance the hardened properties of the concrete, making the concrete less permeable and durable. Hence, optimized quaternary blended concrete mixes are preferred for concrete overlay projects using ultra-thin white topping concrete,

which makes a project sustainable.

5. Further, it was concluded that research on quaternary sustainable material blended concrete mixes for concrete overlays helps reduce the cement content, thereby reducing carbon dioxide emissions, enhancing the fresh and hardened properties of the concrete making the concrete and mix durable with better long-term performance. So, these concrete mixes for ultra-thin white topping concrete overlays address the economic point of view with the inclusion of sustainability concept which was the subject of global construction industry's attention.

**Acknowledgments**

The authors are thankful to Bapatla Engineering College for providing testing facilities and valuable support in conducting this research.

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