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ELECTRICALLY CONDUCTIVE CONCRETE

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Abstract: Concrete has been known for decades as a non-conductive material. However, electrically conductive concrete is an innovative type of concrete, which incorporates conductive material to form a contiguous network of current flow. Such materials include graphite powder, steel shavings and steel fibers. This new mix offer a spectrum of applications such as de-icing on bridges and runways, cathodic protection, radiant heating and electromagnetic shielding. This study aims at exploring means to prepare conductive concrete together with achieving better understanding of the properties and performance of conductive concrete made with three potentially conductive materials at different dosages. To meet this objective, concrete mixes were prepared with various presumably conductive materials. The testing scheme includes conventional fresh and hardened concrete tests as well as specialized conductive and permeability tests. Results reveal that producing conductive concrete is possible through various means. However, care has to be taken that such mixes require thorough mixing and incorporation of materials. Initial findings suggest that conductivity is a function of both the type of the materials and dosage incorporated. The findings of this study are promising and should be built upon in order to propose such new concrete types in conductive media construction applications.

1 INTRODUCTION

Conventional concrete is known and used as an insulating material, however nowadays by making concrete conductive several advantages were seen that could be applied to several applications. Conductive concrete was first investigated in 1970's and 80's. Over the years, several mixes were experimented using different electrically conductive materials. Some of these materials are graphite powder, carbon particles and steel shavings, which is a waste material from steel industries. Adding any of these materials to the concrete mix will change the concrete's properties. These properties include but not limited to compressive strength, flexural strength, water permeability, electrical conductivity and heating rate. Moreover, new properties are expected to be found in this concrete, which will able us to use it in new applications such as de-icing on bridges and runways, cathodic protection, radiant heating, electromagnetic shielding and electrical grounding. To produce conductive concrete, the concrete is mixed with a suitable dosage of the conductive material so that a contiguous network of current flow is formed. The dosage should be enough to allow the concrete to be electrically conductive while maintaining adequate mechanical properties of the concrete.

2 LITERATURE REVIEW

2.1 Carbon and Graphite products for conductive concrete

The Roca Spur Bridge was the first implementation that used conductive concrete in bridge deck de-icing, Seven commercial carbon and graphite products were used to create 10 different mixtures with different dosages for comparison and evaluation, the mixtures included black diamond which is the trade name of a natural graphite crystalline in the form of pellets, Earth Link (EL) which is the trade name of graphite cement, which is made up of approximately 70% Portland cement and 30% graphite powder. Finally, EC, which is elemental carbon, was used with different particle sizes.

2.2 Steel Shavings and steel fibers for conductive concrete

A research was conducted in the University of Nebraska to test the de-icing capabilities of conductive concrete. In the research Christopher Y. Tuan, 2004, constructed a simulated bridge deck using conventional reinforced concrete of an area of 1.2 x 3.6 m (4 x 12 ft.) and 152 mm-thick (6 in.). After the bridge deck was constructed, conductive concrete was casted over the reinforced concrete slab to form a new slab of thickness 90 mm. The conductive concrete mix, which was developed at the University of Nebraska, contained 1.5% of steel fibers and 20% of steel shavings per volume. The steel fibers and shavings that were added to a regular concrete mixture aimed to achieve the required electric resistivity for electrical resistance heating. Two 64 mm-wide (2.5 in.) and 6 mm- thick (0.25 in.) steel plates were embedded along the length of the overlay for electrodes. The steel plates had perforations greater than or equal to the 13 mm (0.5 in.) maximum aggregate size to allow concrete to flow through to provide good anchorage in the overlay.

2.3 Conductive concrete applications

Xie et al, 2004, used carbon fibers and particles for conductive materials in de-icing applications. Shintani and Nakamura developed a conductive concrete mixture for electromagnetic wave shielding. In 1998 at the University of Nebraska, Yehia et al., 2004, developed a conductive concrete mixture specifically for bridge deck de-icing. Other applications are radiant heating where Conductive concrete is used as an indoor radiant heat option, electrical grounding and the first practical project using HCFA concrete was electrically grounding a telecommunications tower in Rudolph, WI. and finally cathodic protection to prevent corrosion of reinforcing steel where the reinforcement becomes in a stable passive state when using a negative protective current since the formation of hydroxide ions on the reinforcement restores the protective passive layer.

3 OBJECTIVE & SCOPE

In this research, the main objective was to evaluate the potential of producing conductive concrete that can be implemented with various conductivity levels in diverse applications. To meet this objective, a conventional concrete mix was used as a control to test three different materials, which are steel fibers, steel shavings and graphite powder with different dosages for each material and compare all the results to get a better understanding of conductive concrete.

4 EXPERIMENTAL PROGRAM

4.1 Material Properties

- Fine Aggregates: well graded sand, sieved on sieve no. 4, used as fine aggregate with specific gravity
- Coarse Aggregates: well graded crushed limestone used as coarse aggregates with specific gravity
- Water: normal tap water was used for the mixes and curing.
- Cement: Ordinary Portland cement, Type I
- Super plasticizer: Super plasticizer Type F
- Steel Fibers: 50 mm x 1 mm end-hooked steel fibers with minimum tensile strength 1000 N/mm2

- Steel Shavings: Steel Shavings of different sizes and shapes contaminated with oil and other foreign elements.
- Graphite: very fine graphite powder produced by a local factory.

4.2 Concrete Mix design

The concrete mix used in the experimental work of this study consists of nine different mixes including the control mix and three mixes with different dosage for the steel fibers and steel shavings, and two mixes for the graphite powder. The nine mixes are shown in table 1. The cement dosage was 400 kg/m3 and a fixed water-to-cement ratio of 0.5 was used throughout all the mixes. The material added replaced the aggregates by volume with a fixed ratio of 1:1.8 of the fine aggregate to the coarse aggregate. An air content of 3% was assumed before the testing and adjusted according to the super plasticizer needed.

Table 1: Mix Design

Mix	Property	Cement (kg)	w/c	Water (kg)	Coarse (kg)	Fine (kg)	Material (m3)	Super Plasticizer (liters)
1	Conventional concrete (Conv.)	400	0.5	200	1099	611	0	4
2	Steel Fibers 1% (SF1)	400	0.5	200	1050	583	10	4
3	Steel Fibers 1.5% (SF1.5)	400	0.5	200	1042	579	15	8
4	Steel Fibers 2% (SF2)	400	0.5	200	1033	574	20	8
5	Steel Shavings 10% (SS10)	400	0.5	200	899	499	100	12
6	Steel Shavings 15% (SS15)	400	0.5	200	815	453	150	12
7	Steel Shavings 20% (SS20)	400	0.5	200	724	402	200	6
8	Graphite Powder 5% (GP5)	400	0.5	200	983	546	50	8
9	Graphite Powder 15% (GP15)	400	0.5	200	822	456	150	4

4.3 Standard Tests

4.3.1 Fresh Tests

These tests included slump, unit weight, air content and temperature. Slump was done to measure the workability of the mix, Unit weight was used to measure the density of the freshly mixed, Air content is used to determine the air content of freshly mixed concrete without any air voids that may exist within the aggregates. Finally, temperature test measures the temperature of the concrete using a temperature-measuring device

4.3.2 Compressive Strength

This test was conducted to evaluate the compressive strength of each type of concrete using 150x150x150 mm cubes. For each of the nine types of cement, three cubes samples were taken on each age of testing.

4.3.3 Flexural Strength

Beams of 750x150x150 mm were tested to find the flexural strength after 28 days. For each mix, two beams were tested under center-point loading.

4.4 Specialized Tests

4.4.1 Water Permeability

In accordance with the German standard DIN 1048, three cubes of 150x150x150 mm were tested to determine the susceptibility of an unsaturated concrete to the penetration of water. The test is carried out after 28 days by putting the specimen over a water jet for 72 hours.

4.4.2 Conductivity Test

This test was conducted in order to determine the electrical resistivity and hence conductivity of the different mixes. This test has no standardized reference. Therefore, the specimen dimensions and test setup were empirically selected. The specimens for the test were 90x30x10 cm slabs (1 for each mix). Two nails were cast on opposite sides within the slab. The setup works by connecting the main AC power supply to a step-down & up transformer. An ammeter is connected in series, followed by a light bulb which was introduced in order to determine the minimum voltage required to induce sufficient current in order to light a bulb. This wire is then connected to one of the nails in the slab, and another wire is connected to the opposite nail, which goes back to the transformer to end the circuit. Through studied literature review, it was expected that the resistivity of the material would increase throughout time. Accordingly, readings for the voltage and current were taken every week for a period of three months to monitor the change in the material properties.

Figure 1: Slab for testing

Figure 2: Laser Gun

4.4.3 Heating Rate test

This test aimed to determine the rise in temperature per time for one of the best conducting mixes. The initial setup was composed of a thermocouple wire, which, was cast within every slab in order to measure the internal temperature of the various mixes. However, this set-up did not prove effective because the current moved in the thermocouple wire itself and caused the reader to give false results. The second method used the help of a laser gun, which can measure the surface temperature of any material. The purpose of this test was to study the effect of passing current through one of the best conducting slabs.

4.4.4 Graphite water absorption

The test was carried out by mixing a small amount of the graphite powder with water, and then allowing it to dissipate the water through a filter paper. The powder was weighed before and after the test and an absorption percentage was determined.

5 RESULTS & ANALYSIS

5.1 Fresh Tests

5.1.1 Unit Weight

The unit weight as illustrated by the results was found to be slightly lower in the graphite mixes than the control mix as the graphite has lower specific gravity than the aggregates it replaced, and also because the water added for the graphite absorption. The steel shavings seem to increase the unit weight significantly due to their high specific gravity. On the other hand, the steel fibers increased the unit weight of the concrete in the first mix, however by increasing the fibers percentage, the unit weight decreased. This is consistent with the air content values, as the percent of the material increases, more air is entrapped within the mix decreasing its unit weight.

5.1.2 Slump

In order to get good workability levels of the mixes, the super plasticiser was added with different dosages to each mix as shown in the mix design. All the slump results were in an acceptable range but more research have to be done in order to reach the optimum workability level of each mix.

5.1.3 Air Content

Results showed that the air content in the graphite mixes were within the normal range, however for the steel fibers it was higher due to insufficient compaction and in the steel shavings the air entrapped was the highest due to the shape of the shaving as it is spiral and may have caused the air to be entrapped. Also, insufficient compaction might be a factor.

5.1.4 Temperature

All the mixes temperatures are within the normal range of fresh concrete's temperature

Table 2: Fresh tests results

	Conv.	SF1	SF1.5	SF2	SS10	SS15	SS20	GP5	GP15
Unit weight (kg/m3)	2471	2575	2437	2109	2604	2843	2614	2397	2142
Slump (cm)	11.5	2	17.5	13	15	5	10	22	7
Air content (%)	1.5	1.9	2.5	3	1.1	4	3.8	1.8	1.6
Temperature (°C)	23.7	25.7	23.9	23.8	22.9	22.9	25	25	25.4

5.2 Hardened Tests

5.2.1 Compressive Strength

The results of the compressive strength test are shown in figure 1. It shows that the concrete mix with steel fibers have the highest compressive strength reaching more than 45 MPa after 28 days. It also shows that the mixes containing steel shavings or graphite powder decrease the strength of the concrete relative to the control mix. The high percentage of water absorption of the graphite powder is the main reason for the decrease in the strength. None of the mixes containing steel shavings or fibers reached a strength more than 25 MPa. The minor irregularities in the results could be due to insufficient compaction.

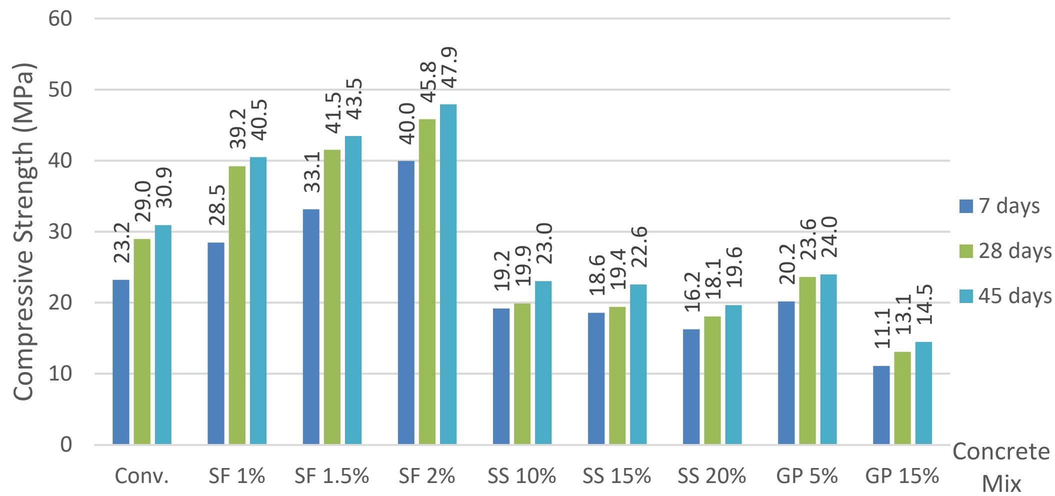

Figure 3: Compressive strength results

5.2.2 Flexural Strength

Figure 4 illustrates the flexural strength in MPa for the mixes, which is similar to the results of the compressive strength showing that the mixes containing steel fibers attain the highest strength of 13.8 MPa compared to 8.8 MPa for the conventional concrete. The fibers mixes exhibited ductile failure while the other mixtures collapsed and split. On the other hand, the steel shavings decrease the flexural strength of the concrete mix reaching similar results ranging between 6.1 & 6.3. The graphite also decreased the flexural strength significantly reaching 3MPa for the graphite 15% mix. The high percentage of water absorption of the graphite powder is the main reason for the decrease in the strength.

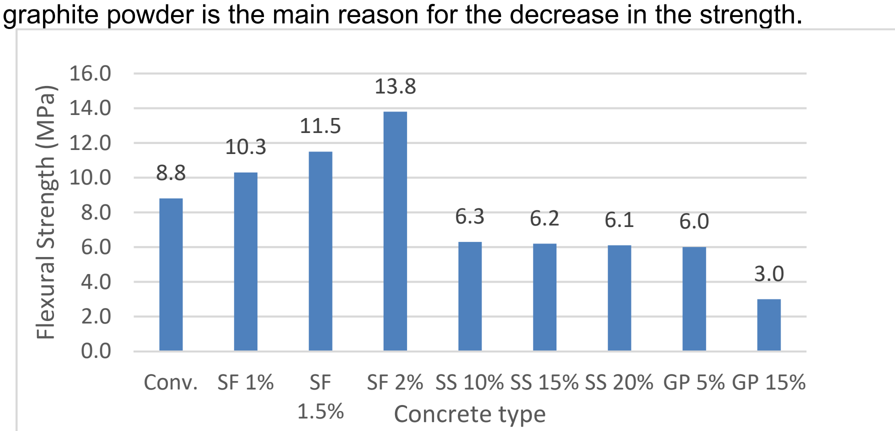

Figure 4: Flexural strength results

5.3 Specialized Tests

5.3.1 Water Permeability Test

The water penetration test results show a clear trend for all the materials. Given the conventional concrete mix as our datum, the graphite seems to lower the water penetration of the concrete due to its fineness as it fills out all the gaps and the voids in the mix. As graphite percentage increases in the mix, the water penetration decreases.

As for the steel shavings, they resulted in a high water penetration reaching 7cm penetration for the mix containing 20% shavings. This result could be due to the air entrapped inside the mixes, which is caused by the different sizes and shapes of the steel shavings.

Finally, the steel fibers show promising results. Compared to the conventional concrete, they also lower the water penetration reaching 0.5 cm for the 1% fibers.

Table 3: Water permeability test results

Mix	Water Penetration (cm)
Conv.	3.5
SF 1%	0.5
SF 1.5%	0.8
SF 2%	1.3
SS 10%	6.5
SS 15%	6.5
SS 20%	7
GP 5%	1.9

5.3.2 Conductivity Test

Displayed below are the equations used in order to determine σ, the electrical conductivity, for each mix.

[1] $R = \frac{V}{I}$

Where V is the voltage in volts, I is the current in amperes and R is the resistance in ohms.

[2] $\rho = \frac{V}{I}(\frac{wt}{L})$

Where ***ρ*** is the electrical resistivity in ohm-cm, w, t, & L are the width, thickness, and length of the specimen respectively

[3] $\sigma = \frac{1}{\rho}$

σ is the electrical conductivity in 1/ohm-cm

In an attempt to further understand conductive concrete properties and the application of different materials together, a new slab, which includes two maximum dosages of two different materials (15% graphite powder & 2% steel fibres), was cast and tested for conductivity.

Displayed below are the results for the electrical conductivity for all tested materials with time.

Table 4: Conductivity after 28 Days

Mix	V (V)	I (A)	R (Ω)	***ρ*** (Ωcm)	σ (1/Ωcm) x10-3
CC	310	0.08	3875	15500	0.065
GP 5%	200	0.09	2222	8889	0.113
GP 15%	110	0.09	1222	4889	0.205
SS 10%	188	0.09	2089	8356	0.12
SS 15%	182	0.09	2022	8089	0.124
SS 20%	135	0.09	1500	6000	0.167

Mix	V (V)	I (A)	R (Ω)	***ρ*** (Ωcm)	σ (1/Ωcm) x10-3
SF 1%	130	0.09	1444	5778	0.173
SF 1.5%	38	0.09	422	1689	0.592
SF 2%	27	0.09	300	1200	0.833
GP 15% SF 2%	9.9	0.09	110	440	2.273

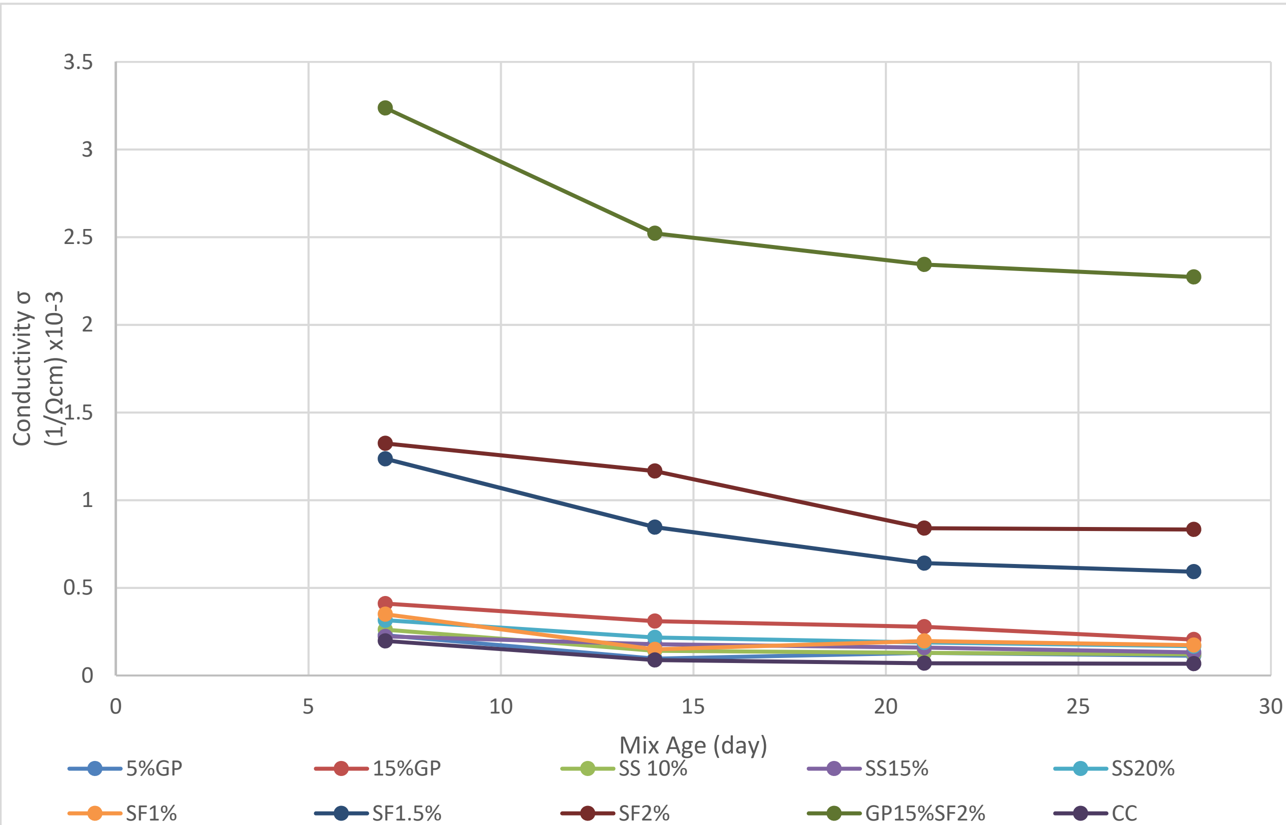

Figure 5: Electrical conductivity results for all mixes

Analysis:

The graph shows the conductivity vs. time for the different mixes. Overall, all tested materials (graphite powder - steel fibres - steel shavings) yielded higher electrical conductivity results than conventional concrete. The most conductive mixes from those containing one material were the steel fibres with dosages of 1.5% and 2%. The results for the mix containing 1% steel fibres are farther from the higher dosages but are still higher than the results for different materials. The results for graphite powder and steel shavings show less conductive behaviour and relatively lie in the same area, which is close to conventional concrete. The graph also shows the results for the special slab, which contains 15% graphite powder and 2% steel fibers, compared to the rest of the mixes, which contain only one type of material. This mix yielded much higher results for electrical conductivity, yet, further testing needs to be carried out in order to determine its mechanical properties and durability.

Although the results have a common trend and continue to decrease with time, all tested materials yielded higher electrical conductivity than conventional concrete. This phenomenon occurs due to the loss of water (which is an electrolyte) from the concrete and its replacement by air.

5.3.3 Heating Rate Test

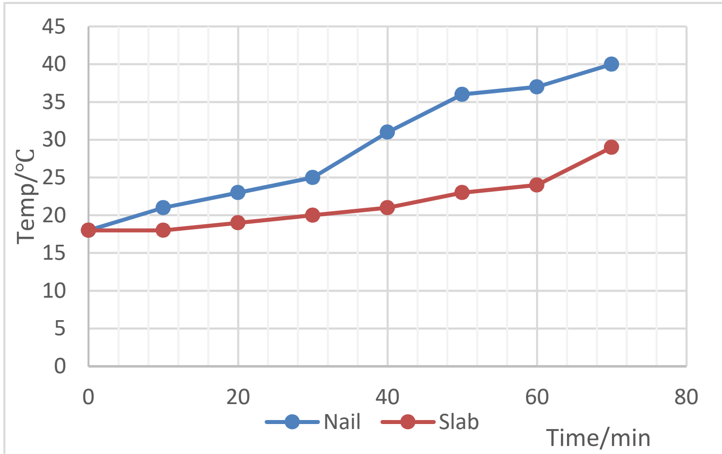

Figure 6: Surface temperature vs. time for mix containing 2% steel fibers

Analysis:

The heating rate test was carried out in order to explore the effect of passing current through the concrete. The test was carried out on one mix only, fibers 2%, which had the highest results for electrical conductivity. Readings for surface temperature were taken every 10 minutes for a period of 70 minutes

6 COST ANALYSIS

Table 5: Cost analysis

Mix	Cost of Material L.E/kg	Estimated Cost of Mix L.E/m3
Conventional Concrete		756
Fiber 1%	16	1781
Fibers 1.5%	16	2390
Fibers 2%	16	2908
Steel Shavings 10%	5	3379
Steel Shavings 15%	5	4511
Steel Shavings 20%	5	5687
Graphite 5%	11	1967
Graphite 15%	11	4226

7 CONCLUSIONS

In light of our research and after performing several tests on the mixes results were obtained that led to these conclusions:

- Electrical conductivity results show that mixes containing steel fibers are the most conductive followed by both the graphite and steel shavings which show relatively close conductivity results
- The limited feasibility study demonstrates that steel fibers are the most economic material in comparison with the other conductive materials tested
- The steel fibers have significantly increased the compressive strength and flexural strength of concrete
- The graphite powder decreases the unit weight of concrete
- The mixes containing graphite powder requires more water to account for the graphite absorption

- From the graphite mixes better finishability was obtained than the steel fibers and steel shavings mixes
- Graphite mixes are the least water permeable which is due to the high fineness of graphite powder

8 RECOMMENDATIONS

For further research:

- Larger scope of experimental work should be performed on reinforced concrete
- Conduct further tests such as rapid chloride permeability test (RCPT), chemical durability and thermal heating
- Use more reliable and higher accuracy set up for the heating rate test
- Test conductive concrete using voltages higher than 220 volts
- Use different dosages of materials together for further testing
- Acquire steel shaving waste from different sources to test different types of steel shavings considering that it is a waste material which can vary from one source to another

For Applicators:

- Adjust the dosages of the super plasticizer
- Mix the mixes containing steel fibers for an adequate time to reach a homogenous mix
- Increase darbying and vibration in steel fibers & shavings to ensure a smooth finishing surface
- Allocate more time for cleaning the steel shavings to avoid the reaction between any contaminants and the concrete components
- Allocate more time for sieving the steel shavings to have relatively close sizes throughout the mixes
- Coat steel shavings with zinc to prevent rusting
- Cover the mixer during the mixing process of graphite powder to limit the dispersion of the fine powder

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