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Producing 100+ MPa Field Concrete in Developing Countries: Requirements and Challenges

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Abstract. Over the past three decades, there has been a paradigm shift in the concrete industry in which high strength and high performance concrete became more widely in use. However, producing ultra-high strength concrete surpassing 100 MPa compressive strength in the field remains a challenging task. This is primarily due to the various factors involved in such concrete and its sensitivity to many of these factors. This study aims at producing field concrete surpassing 100 MPa compressive strength using readily available materials worldwide. The study also addresses the requirements and challenges of 100+ MPa concrete in the field in order to possess similar properties to conjugate mixtures produced in the laboratory having same mix proportions. Concrete mixtures were prepared with different water-to-cement ratios and incorporated variety of chemical and mineral admixtures. Tests included fresh concrete, self-consolidation as well as hardened concrete properties in order to determine the properties of the concrete produced. The impact of other vital factors such as mixing process, ambient temperature, curing process and pumping are addressed taking field conditions into consideration. Several field visits were conducted to monitor field concrete that was produced using the designated mixtures. The study herein revealed that reaching 100 plus MPa concrete is doable using variety of readily-available constituents and mix proportion. However, the study pinpoints the importance of other crucial factors and field practices. Recommendations are provided to concrete users and practitioners to exercise better quality control and ensure high rate of success in producing ultra-high strength concrete in the field.

Key words: Concrete, 100+ MPa Concrete, Field Challenges, Ultra High Strength

1. Introduction

High Strength Concrete is a term that has evolved and developed over the past decades as a result of advances in concrete materials and technology. The term was first used in the 1950's, where compressive strength reached 34 MPa or higher. Over time, this threshold has increased both in laboratory as well as in field applications. Due to advancements in the newer generations of chemical admixture, availability of mineral admixtures, and a multitude of advantages rendered, the demand for high-strength concrete particularly in high-rise buildings and strategic structures has increased. While still not widespread worldwide, high strength concrete is gradually becoming more of the norm than the exception. For instance, the need to increase the structural capacity can now be achieved by increasing the concrete strength rather than increasing the size of the structural elements themselves (Ranade et al., 2017; Senthilkumar & Asvinth, 2020). During the last three decades, high strength concrete and ultra-high strength concrete with strengths surpassing 100 MPa were produced. This helped in minimizing the design cross sections and steel reinforcement among other advantages. When doing so, the gain of adopting these new concrete types is not limited to the increase in strength. Rather, it is well established that high strength concrete possesses better durability and extended service life (Okamura, 1997). Moreover, high strength concrete generally has higher toughness and tensile ductility, when compared with conventional concrete accompanied with an enhancement in abrasion resistance, impermeability, and lower water absorption (Ranade et al., 2017; El-Sayed et al., 2011). Later, very high strength concrete (VHSC) was introduced in the early 1990's, which refers to concrete that has a compressive strength higher than 150 MPa (Richard & Cheyrezy, 1995). Having such high compressive strength, VHSC paved the way for many specialized applications including members in mass concrete structures that require size efficiency and strategically critical structures that require additional strength safety margin (Neeley & Walley, 1995; O'Neil III, 2008). The focus on performance in addition to strength led to the development of the terminology ultra-high performance concrete (UHPC). The term UHPC has been occasionally interchanged with the term ultra-high strength concrete (UHSC). Such superior concrete mixtures are considered as more sustainable materials and hence their use has been growing (Azmee & Shafiq, 2018). The improved durability and extended service life take this concrete steps closer towards green and sustainable construction which have tangible positive environmental impact.

To achieve higher strength, concrete mixtures usually have high cementitious content, high fine aggregate ratio, make use of mineral admixtures together with high dosage of high-range water reducing admixtures. To improve consistency and homogeneity and minimize stress concentrations, the use of large-sized coarse aggregates is reduced. Effective mineral admixtures, often more than one type, are needed to provide effective pozzolanic reactions, introduce low permeability and enhance cohesiveness. The use of low water-to-cementitious materials ratio (w/cm) is also crucial. In this type of concrete, water to cementitious material ratio is usually below 0.35 in these mixtures. In fact, in many cases, w/cm of 0.20 or slightly lower were used (Richard & Cheyrezy, 1995; Collepardi et al., 1997; Roux et al., 1996). Proper production of UHSC requires thorough selection of constituent materials and adjustments of their proportions in the concrete mix (Ravitheja et al., 2021; Abbas et al., 2016; Pertiwi et al., 2023). Due to the low water content in UHPC, good curing is essential for its success as documented by several practices (Abbas et al., 2016). Together with all technical aspects, skilled labor and close supervision are essential to the production of UHSC.

On a global scale, the use of ultra-high strength concrete remains somewhat limited due to multiple factors. This includes high initial material cost, lack of experience of contractors and applicators together with outdated design code provisions (Abbas et al., 2016). To give one example, in the entire African content, there are no code provisions for concrete with strength surpassing 60 MPa. Also, there is a lack of awareness and "know-how" for achieving UHSC not only in the laboratory but in actual field conditions.

Producing field UHSC, such as concrete surpassing 100 MPa, is a doable task that requires adequate planning, good field practices, and ability to adjust the concrete production in light of ambient conditions and project requirements. There are many structures around the world that were built using 100+ MPa concrete. However, in many parts of the world, there is scarcity of data regarding the requirements and challenges associated with UHSC. Also, there is no sufficient knowledge about readily available market materials needed for their production.

The main objective of this work is to provide recommendations for producing field concrete with compressive strength surpassing 100+ MPa using various mix proportions using constituents that are readily available in the Egyptian market, as an example of developing countries. Requirements and challenges facing the production of this type of concrete are discussed, taking actual field conditions into consideration. The aforementioned objective was met through the following:

- Designing and performing a laboratory experimental program that is later mapped to field practice.
- Conducting field visit and monitoring of actual concrete produced using similar mixtures to the ones proposed by this study.
- Presenting recommendations based on previously published case studies.

2. Experimental Work

2.1. Concrete Material Requirements

The choice of materials for use in this study focused on choosing materials that are readily available in the Egyptian market. The materials were selected to have good quality that meets ASTM standards and good concrete practices.

- Portland cement was an ASTM Type I ordinary Portland cement with Blaine fineness of 340 kg/m^2 and specific gravity of 3.14.
- The fine aggregate used was river sand with saturated surface dry (SSD) specific gravity of 2.55 and fineness modulus of 3.01.
- The coarse aggregate used was well-graded angular dolomitic limestone sized (14-20 mm) and specific gravity of 2.59. All aggregates have been washed prior to their incorporation into concrete to get rid of the surface fines.
- Densified silica fume (Microsilica) was used. The material had a specific gravity of 2.21 and a minimum SiO_2 content of 93%. The material was added at a dosage of 9 to 11% by weight of Portland cement. This range was selected because the recommended dosage in literature is around 10% (Suda & Rao, 2020).
- Superplasticizer was an ASTM C-494 (ASTM,1999). Type G admixture (ME 3977). The Superplasticizer was added at a dosage of 2% by weight of cementitious materials.
- Municipal water was used in laboratory, as well as in field concrete production.

2.2. Concrete Mix Proportions

Seven concrete mixes were prepared to investigate the effect of the different properties on the performance of concrete while targeting 28-day compressive of 100 plus MPa. All mixtures had the same amount of Portland cement (500 kg/m^3) while water-to-cementitious material ratio (w/cm) varied from 0.24, 0.28 and 0.30. The amount of Microsilica used varied accordingly to be 45 kg/m^3, 50 kg/m^3 and 55 kg/m^3. Finally, the amount of admixture used, which was in the range of 1.5-3.0% by weight of cement, was based on the workability of the concrete and slump flow test. The seven mixes are presented in Table 1.

Table 1 - Key characteristics of the concrete mixtures

Constituent	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Cement (kg)	500	500	500	500	500	500	500
Microsilica (kg)	50	55	45	50	50	45	55
w/cm ratio	0.30	0.30	0.30	0.24	0.28	0.24	0.24
Admixture (liter)	10	9	7.5	13	9.5	14.5	15

2.3. Laboratory Testing

The testing conducted in the laboratory to study the performance of the seven mixes was divided into two groups, fresh concrete testing and hardened concrete testing.

Fresh Concrete Testing

The following tests were conducted on fresh concrete to study the behavior of each of the seven mixes investigated in this study:

- Slump Flow: This test was conducted to evaluate the consistency/workability of freshly made concrete. The test was conducted in accordance with ASTM C1611 (ASTM, 2005).
- Air content: This test was conducted to determine the air content of concrete. The test was conducted in accordance with ASTM C231(ASTM, 2004).
- Unit weight: This test was conducted to determine the unit weight of concrete.
- Temperature: This test is conducted to determine the temperature of fresh concrete shortly after mixing.

- L-Box and V-Funnel: These tests were used to assess the “passing ability” of the concrete as “self-consolidating” concrete to flow through tight obstructions without segregation or blocking. The test was performed in accordance with EN 12350-10 (EN, 2010).

Hardened Concrete Tests

The following tests were conducted on hardened concrete to study the performance of each of the seven mixes investigated in this study:

- Compressive Strength: This test was conducted to determine the compressive strength of concrete 150 mm cubes. The test was conducted in accordance with the British Standards.
- Flexural Strength: This test is conducted to determine the flexural strength of a concrete beam. The test was conducted in accordance with ASTM C293 (ASTM, 2026) on 150x150x750 mm beams using three-point bending test with a clear span of 600 mm.
- Rapid Chloride Permeability: The test was conducted to assess the concrete resistance to permeability of chloride ions according to ASTM C1202 (ASTM, 2012). The authors remain vigilant of the drawbacks associated with this test particular when mineral admixtures are used.
- Water Permeability: This test was conducted to determine the true resistance of concrete against the penetration of water under hydrostatic pressure. The test was conducted in accordance with EN 12390-8 (EN, 2020)

3. Results and Analysis

3.1. Fresh Concrete Results

The previously mentioned fresh concrete tests were performed on the seven mixtures. The results are presented in Table 2. The internal temperature of the concrete was measured to ensure that the temperatures were within the acceptable range. The internal temperature results show that the temperature of all the mixes were within the expected range between 28 and 34°C. The air content values were within the acceptable range for non air entrained concrete. The slump flow results were as expected because the admixture quantity was added according to the required workability. The V-funnel and L-box tests were performed to assess the passing ability of the concrete. These were needed to ensure that the concrete produced is not very sensitive to the compaction on site. The tests evaluate the ability of the concrete to flow through tight obstructions without segregation or blocking. Mixes 4, 6, and 7 failed the V funnel test as the time taken exceeded 15 seconds, which is the maximum time allowed for the concrete to pass through the test apparatus. This result was expected because of the low water to cementitious material ratio used in the mixes and the high ambient temperature. Mixes 1 and 4 failed the L box test by having a blocking ratio greater than the required range of 0.8 to 1 to have the desired self-consolidating properties. Self-consolidating properties are desirable in this study because they reduce the risk of losing part of the laboratory strength in field applications due to poor compaction.

3.2. Hardened Concrete Results

Compressive Strength

According to the results of the compressive strength test presented in Figure 1, all cubes were tested for the 3-day and showed high early compressive strength as an effect of the admixtures used. The goal of the mix selection was to achieve a minimum compressive strength of 100MPa after 7days. Any mix that did not achieve this compressive strength threshold was eliminated from the study and was not tested at 28 days. For the 7-day results, Mixes 4,5,6,7 are the only mixes that exceeded the 100MPa threshold after 7 days. These mixes are the mixes that had the least water to cement ratios. Mix 1 was eliminated although its average compressive strength was

101MPa because it was a borderline case. The 7-day compressive strength values reported for mixes 4 through 7 are lower than the actual strength of these mixes. This was due to the limited capacity of the testing machine used and the samples did not reach failure. To overcome this problem, the samples used for 28-day strength testing were 100 x 100 x 100 cubes to avoid exceeding the capacity of the compressive testing machine. To correct for smaller sized cube, factor of 0.95 was multiplied by the compressive strength result. The compressive strength results showed that the compressive strength was highest for the mix 4 which had a low water to cement ratio and high amount of Microsilica as shown in Figure 1.

Table 2 - Fresh concrete results

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Air Entrainment (%)	0.9	1.5	1.4	2.2	1.3	2.0	1.8
Unit Weight (kg/m^3)	2417	2426	2420	2483	2437	2474	2451
Slump Flow (cm)	67	62	64	56	66	57	62
V Funnel (Seconds)							
10 sec	5.55	14.53	11.98	Test Failed	9.88	Test Failed	N/A
5 min	9.73	19.98	14.62		13.04		
L-Box (cm)							
Result Bottom	8.8	8.43	8.37	Test Failed	8.17	8.17	8.37
Result Top	8.2	9	9.13		9.83	8.13	8.87
Blocking Ratio	Test Failed	0.94	0.92		0.83	1	0.94

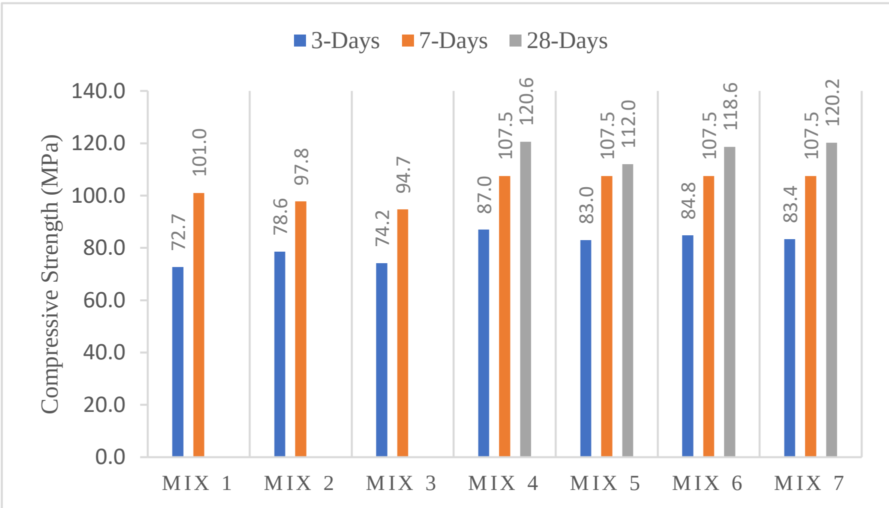

Fig 1. Compressive strength results

Flexural Strength

The results of the flexural strength are presented for the different concrete mixes at 28 days in Table 2. The tests were performed on beams of size 600x150x150 mm. The lowest flexural strength of the 7 mixes was in Mix 5. The results showed that the ratio of the flexural strength to the compressive strength results ranged between 0.08 to 0.12, highlighting the huge difference between the flexural and compressive strength, respectively.

Table 3. Comparison between compressive and flexural strengths

	Mix1	Mix 2	Mix3	Mix 4	Mix 5	Mix 6	Mix 7
Flexural (MPa)	11.8	10.9	12.6	14.0	9.4	13.3	14.1
Compressive (MPa)	N/A	N/A	N/A	120.6	112.0	118.6	120.2
Flexural/Compressive Strength Ratio	N/A	N/A	N/A	0.12	0.08	0.11	0.12

The equation provided in the Egyptian code of Practice (ECP) for calculation of concrete flexural strength (Equation 1) was used to estimate the flexural strength of the tested mixes.

$$Flexural\ Strength = 0.67\sqrt{Fcu} \qquad (1)$$

Where:

F_{cu} = 28 day compressive strength (MPa).

The use of the ECP equation produced flexural strength values between 4.5 and 5.5 MPa. These values were very small in comparison to the values acquired from laboratory testing, which ranged from 9.4 to 14.1 MPa. The results are presented in Table 4. This shows that the ECP equations are not designed for ultra-high or high strength concrete. Thus, while designing UHSC it is preferred to use adjusted equations to accommodate the difference.

Table 4. Flexural strength comparison between ECP and lab results

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
According to ECP Formula (MPa)	5.1	4.8	5.2	5.5	4.5	5.4	5.5
Laboratory Results (MPa)	11.8	10.9	12.6	14.0	9.4	13.3	14.1

Rapid Chloride Penetration Results

The rapid chloride test determines the resistance of a concrete sample to the penetration of chloride ions. All the samples produced very low or negligible results according to ASTM designation as presented in Table 5. Thus, indicating high resistance to chloride ions. This is expected as the characteristics of the high strength concrete include low permeability and high durability.

Table 5. Rapid chloride penetration test results

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Sample 1 Results (Coulombs)	64	138	245	167	65	53	55
Designation	Negligible	Very Low	Very Low	Very Low	Negligible	Negligible	Negligible
Sample 2 Results (Coulombs)	92	85	126	47	73	66	68
Designation	Negligible	Negligible	Very Low	Negligible	Negligible	Negligible	Negligible

Water Permeability

The water permeability test determines the true resistance of concrete against the penetration of water under hydrostatic pressure. The results of the water permeability test are presented in Table 6. Most of the mixes did not get penetrated by water except Mixes 4 and 5, which were very minimally penetrated by 1.2 and 0.8 cm, respectively. The penetration of these 2 mixes is minimal and are within the acceptable range.

Table 6. Water permeability test results

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Water Penetration (cm)	0	0	0	1.2	0.8	0	0

4. Field Factors Affecting Concrete Properties

As presented in the previous section, several mixes were capable of achieving the desired strength using materials that are readily available in the Egyptian market. The main challenge is to produce field mixes that can achieve the same performance in the field. In order to study the main factors affecting the production of concrete with strength exceeding 100 MPa, the researchers conducted interviews with the concrete producers who are producing concrete for an ongoing project in the New Egyptian Administrative Capital, which is currently under construction. The results were then verified by supporting literature. The main challenges that were identified are presented in this section.

4.1. Ambient Temperature

High ambient temperature affects greatly the hydration process of concrete. This causes the amount of water in the mix to evaporate leading to hardening in concrete without achieving the desired strength and losing workability. This process is called early stiffening and erratic setting (Allena & Newtson, 2011). It is mainly the process when the concrete starting stiffening before it starts setting. This is a problem of major concern for both producers and purchasers specially during hot weather. This can be caused by many factors including: Low w/c ratio, high ambient temperature, and very fine cementitious material, which are all present in creating Ultra high strength concrete. This results in a great loss in workability and thus, one solution is the adding admixture to the concrete mix to recover the workability lost.

4.2. Mixing

There are three methods of concrete mixing; Central Mixed Concrete: This mixing in this method is done in a stationary mixer and its delivery utilizes agitator trucks. Shrink Mixed Concrete: The mixing in this method is partially done in a stationary mixer and finished in truck mixers. Truck Mixed Concrete: The mixing in this method is completely mixed in truck mixers. The Central Mixed Concrete is the best option for concrete with strength exceeding 100 MPa, since it provided the necessary consistency and control. On the other hand, this procedure depends massively on the quality of the work from the labor producing the concrete. The mixing process should be done in a time span between 90 to 120 seconds and a rate of 15 to 18 rpm. In addition, the ideal temperature of the concrete should be between 24°C and 30°C, as it ensures that the concrete has the best workability. The only chemical admixtures that are used are the ones that increase the workability. In fact, it should be ensured that all admixtures used for the mixing and the workability are from the same manufacturer and of the same type. To maintain the workability, two or three dosages of admixtures should be added when needed. Indeed, the second dose will affect the slump flow whilst the compressive strength will remain unchanged (Maanser et al., 2018). For the full compaction condition, the lower the water/cement ratio, the less water added, the higher the strength of the concrete. On the other hand, the fluidity of the mixture will decrease if the water/cement ratio is low which will cause issues in the compaction where the concrete strength will decrease.

4.3. Placement

There should be no delays in the delivery process (Caldarone, 2014). A professional should supervise everything and make sure that the process is done following the required plan and that no individual should try to the increase the workability by adding water. This is an issue that appears when the involved labor is not used to high strength concrete and its dryness. In fact, adding water will be detrimental to the strength of concrete. For the placement of the concrete, pumping is the best option. In most cases, the permissible time from batching to placement can usually be limited to 90 minutes. However, Limiting the allowable placement time to a shorter period, such as 60 or 75 minutes might be necessary under hot weather conditions, which is the case in Egypt. The Placement of the concrete must be done in order not to cause segregation in the components of the concrete and full consolidation should be achieved with all the air voids eliminated. If full consolidation is not achieved, the compressive strength drops greatly as high strength concrete is more sensitive to compaction.

4.4. Pumping

Pumping pressure affects the properties of fresh concrete (Shen et al., 2021). The pressure based on previous projects done for high rise building using high and ultra-high strength concrete ranges from 220 bar to 360 bar, while the pressure used in conventional concrete is under 170 bar and the diameter sizes ranges from 15 to 15.5 cm (150-155 mm) to accommodate a maximum aggregate size of 20 mm (Caldarone, 2014). The admixture used in the high and ultra-high strength concrete is not a normal superplasticizer, a high retention type super plasticizer is used. A Polycarboxylate-based superplasticizer, which helps in maintaining the high workability of the concrete and having a high slump flow. The compressive strength is affected after pumping in conventional concrete. It can decrease after pumping, however using the Polycarboxylate-based superplasticizer helps in maintaining the strength of the ultra-high compressive strength concrete. It is suggested that during pumping, the migration of moisture happens to the outside of the concrete or inside of the aggregates. Therefore, limestone-based aggregates are often used in UHSC which contributes to enhanced workability, when having low absorption rate.

4.5. Curing

Curing high strength concrete is more critical than conventional concrete (Bushlaibi & Alshamsi). The required strength and durability of the concrete is attained only if it is effectively cured. The difference in compressive strength could change to almost 300% after 3 days when comparing curing with different methods and temperatures (Caldarone, 2014). The hydration reaction of the cement is reduced if the curing water is not provided for the concrete especially that they already have low water to cement ratio. The most effective, but rarely used, method of water curing consists of total immersion of the finished concrete unit in water. Ponding with water is satisfactory for curing whenever a pond of water can be created on the concrete element and so it is an excellent method for curing slabs. However, high strength concrete is mostly used for vertical elements, where this method is not practical to use. Alternately, fog spraying or sprinkling with nozzles would provide satisfactory curing when immersion is not practical. However, it must be considered to prevent sprinkling over irregular intervals as it will lead to thermal cracking, which adversely affects the concrete strength more than not curing at all. Moreover, sprinkling on a continuous basis is suitable, provided that the air temperature is above freezing. Internal moist curing is another method in which additional moisture for hydration is provided from within the concrete without affecting the initial water to cement ratio. It can be done using saturated lightweight aggregates or by adding super absorbent polymers to the concrete. Curing compounds could also be applied as a coating to the surface of concrete to retard the loss of water and could also reflect heat to provide suitable temperature and moisture environment. Curing compounds should be applied as soon as final finishing is complete. Otherwise, they could ruin the concrete's surface. It should also be noted that these compounds retain the original moisture in the concrete but do not provide additional moisture. Finally, formwork removal may need to be delayed in order to prevent thermal cracking. An alternative to this is additional insulation so that the concrete has sufficient strength to resist thermal stresses that could occur if formwork is removed early, especially in cold weather.

5. Conclusions

Based on the materials, techniques, methodology and other parameters associated with this work as well as previously conducted research work, the following can be concluded:

- Producing concrete with strength greater than 100MPa using constituents that are readily available in the Egyptian market is possible. As established in previous work, maintaining low water-to cementitious materials ratio and incorporation of both chemical and mineral admixtures are pivotal in this regard. Choice of high quality materials is also very important.

- Out of the mixtures covered by this work, four mixtures provided satisfactory results and met the targeted strength. Mix 5 made with w/cm of 0.28 yielded better compatibility and self-consolidating performance. This was demonstrated by good V-funnel and L-box results.
- Several of the ultra high strength mixtures produced in this study can be considered as well a form of self-compacting concrete. This adds another dimension to UHPC together with its durability merits. This will also help resolve the risk of losing strength due to poor compaction in the site.
- The interviews conducted, in addition to support from literature, showed that ultra-high strength field concrete is affected not only by materials and mix proportions but also by the mixing process, ambient temperature, placement, pumping, and curing techniques.
- As for pumpability, the addition of polycarboxylate-based superplasticizer along with the sensitive adjustment of pumping pressure are necessary to avoid any drops in workability and during field placement.
- The field concrete produced in this study showed true need to specify a scheme for the batching of chemical admixtures particularly in hot weather. An example, that cannot be generalized, is to add two-thirds of the superplasticizer designated dosage in the mixing plant and later add remaining one-third upon arrival of concrete to site.
- Both the previous work as well as field work conducted by this study team highlight the importance of thorough curing for the field concrete to meet the desired properties.

6. Recommendations

Further work is needed in the future that covers wider spectrum of mix proportions and materials as well as manufacturing techniques. Since one of the key advantages of ultra-high strength concrete is enhanced durability, long-term properties need to be explored and covered by future research work. The human factor; namely the level of skilled labor and supervision need to be incorporated and better addressed in future studies. Finally, a full-scale feasibility study is recommended that should consider direct and indirect costs and take durability and environmental aspects into consideration.

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