Performance evaluation of the quality of CINA cement and BASF admixture commonly used in concrete production in the Republic of Haiti

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ABSTRACT: *A Haitian general contractor and civil engineer was having difficulties achieving the target compressive strength in concrete mixes that are complaint with both regulations and client criteria. An experiment was conducted to assess the quality and performance of CINA cement and BASF PolyHeed 997 water-retarding admixtures commonly used in construction practice in Haiti. The results of this experiment demonstrated that the CINA cement product did not meet adequate compressive strength requirements and can be considered an inferior product when compared to cement manufactured in the United States (U.S.). On average, the compressive strength of final hardened cement was approximately 56% less where using Haitian derived cement in comparison to US-derived cement. Several tests were conducted to understand the impact of curing, cement content and the addition of admixtures to the compressive strength of the final product. Curing was shown to have a significant positive impact on the compressive strength. When the mixtures were subject to air curing only the Haitian-derived concrete did not reach the required target compression strength of 27.6 MPa despite the cement content from the original design was increased by 50% and/or exposed to a setting time of 56 days. The addition of admixture posed no negative effect on the concrete mixtures and did not act as a retarding agent. Significant increases in compressive strength observed for both the Haitian and US-derived mixes. No significant increases in compressive strength when the setting time was increased from 28 days to 56 days. The overarching results of the research demonstrated that the most adequate solution for improving the existing quality of concrete mixtures containing Haitian-derived cement products is to increase the cement content to at least 30% by weight from the original design to achieve the designed compressive strength. It is recommended that the Haitian*

Government, concrete producers, cement manufacturers, and researchers combine their expertise, effort, and resources to produce appropriate solutions to improve the current condition of concrete construction practices in Haiti to increase the robustness of infrastructure design to natural disasters such as hurricanes and earthquakes.

KEYWORDS: *admixtures, cement, compressive strength, concrete, cured, and uncured.*

1 INTRODUCTION

Haiti, like many other islands in the Caribbean, is prone to major natural disasters such as hurricanes and earthquakes. On October 4, 2016, Hurricane Matthew struck southwestern Haiti as a category 4 hurricane with wind speeds of approximately 240 km/h (150 mph)). The impact of this hurricane left widespread damage across the nation resulting in catastrophic flooding of up to 1.0 metre (40 inches) and storm surges of up to 3.0 meters (10 feet) in height (Rice, 2016). Approximately 842 people were killed and more than 28,000 houses were damaged by the effects of the hurricane (IOM, 2016).

On January 12, 2010, a powerful earthquake with a magnitude of 7.0 on the Richter scale hit the south and central parts of the Caribbean island of Haiti. Approximately 250,000 people perished as a result of this earthquake (CNN, 2018) and over 1.5 million Haitians were estimated to be left homeless (USAID, 2011). According to the United Nations Office of the Special Envoy for Haiti, $13.34 billion USD of aid was allocated by international agencies over the time period spanning 2010 to 2020. The United States' (US) Congress authorised a total of $1.14 billion USD for rebuilding Haiti following the 2010 earthquake (Archibold, 2013).

On October 6, 2018, a 5.9 magnitude earthquake struck the northwest of Port-de-Paix on Haiti's north coast, resulting in the death of at least twelve (12) people (Diebel and Bacon, 2018). Prior to the 2010 earthquake, it was recognised that infrastructure located on the island of Haiti was constructed with inappropriate quality of materials and inadequate workmanship (Lang, 2011).

Assessments conducted by engineers and construction experts have concluded that prior to the 2010 earthquake, all concrete structural elements including hollow concrete blocks and columns in infrastructure located on the island was constructed using Type I Portland cement (Lang, 2011). It is therefore, important to evaluate the quality of the cement used in Haiti.

The President of GDG Concrete & Construction, a Haitian general contractor (referred to as "contractor" throughout the paper) and civil engineer with over of 20 years' of experience in concrete manufacturing in Haiti contacted the main author of this paper, a U.S. resident of Haitian descent. The contractor described difficulties he experienced in achieving the target concrete design strength despite the concrete mix being compliant with relevant design regulations and client specific criteria.

In order to evaluate the appropriateness of the concrete material used for construction on the island of Haiti, samples of the Portland Type 1 cement and concrete admixtures were transported from Haiti and subject to testing in the United States. It was hypothesised that the Haitian cement and admixtures were of similar quality to those manufactured in the United States and subsequently would perform similarly when subject to testing.

As the effects of climate change are expected to increase the occurrence and intensity of natural disasters such as hurricanes in the Caribbean region and the United States of America (USA), designing and constructing infrastructure from appropriate materials is imperative in to reduce the risk of fatalities and damage associated with infrastructure failure during natural disasters. It is anticipated that the results generated from this research may serve as guidance for government officials, engineers, and contractors to take adequate measures to develop appropriate cement materials that can withstand the environmental conditions present in the Republic of Haiti and thereby, minimise fatalities and damage associated with infrastructure failure during major natural disasters.

2 OBJECTIVES

The objectives of this research were to:

- Evaluate the current state of the construction practice in Haiti
- Compare the compressive strength of mixes made with Haitian and U.S. cement
- Evaluate the effect of curing on the compressive strength of the mixes
- Analyse the effect of admixtures commonly used in Haiti on the compression strength of concrete samples.

- Conduct a sensitivity analysis to optimise the quantity of Haitian cement for a desirable compressive strength of concrete.

3 LITERATURE REVIEW

On January 12, 2010, an earthquake with a magnitude of 7.0 hit the south and centre regions of the Republic of Haiti. Through all of the extensive death tolls and destruction, one factor was exposed– the building environment was a true weakness in the region. With an in depth look after the earthquake hit, engineers assessed the materials and methods that were used in concrete application prior to the destruction.

Concrete is a mixture of cement, water, coarse and fine aggregates and admixtures (if required). Well-made concrete is a strong, impermeable and durable construction material capable of resisting changes in temperature and wear and tear from weathering and traffic.

Compressive strength is one of the most important engineering properties of concrete and is utilised to compare the performance of concrete in its final hardened state. Typical concrete compressive strengthens in the United States vary by application, with compressive strengths of 20.7 MPa (3,000 psi) used in residential concrete structures and 27.6 MPa (4,000 psi) and higher used for commercial structures. Previous in-situ compression tests conducted on Haitian cement samples have showed average maximum compressive strengths of approximately 11.0 MPa (1,600 psi) with a standard deviation of 2.5 MPa (360 psi) (Lang and Marshall, 2011). For the 28-day compressive strength tests of fresh mix with proper curing, Haitian concrete samples ranged from peaks of 8.7 MPa (1,260 psi) to lows of just 2.8 MPa (410 psi) (Gordon, et al., 2016; Holliday et. al., 2011). These results are comparatively low to the typical design standards required for minimum specified concrete strength in the United States (US) is at 20.7 MPa (3,000 psi) and may be causes of concern, particularly in areas that are subject to extreme environmental conditions.

The properties that affect the strength and durability of concrete include the following:

- type of and proportion of cement
- water to cement ratio
- aggregate type and size
- addition of admixtures
- concrete application and handling (e.g. compaction and curing)

These properties are discussed in more detail below within the context of cement production in Haiti.

3.1 Type and Proportion of Cement in Mixture

Portland cement is limestone derived product and is the most widely used concrete type construction materials throughout the world due to its high durability and its high early strength at a relatively low cost (Khazanovich, et al., 1998). Portland Cement consists of silicates, gypsum, and aluminates from limestone and shale, that forms a paste with the addition of water. Cement is by far the most expensive material as compared to the other components in a traditional concrete mixture.

CINA – Cimenterie Nationale Haiti (Haiti National Cement) is a major producer of cement in Haiti. CINA cement is certified in accordance with the ASTM C1157 Standard Performance Specification for Hydraulic Cement. Type I cement certified under this standard expected to meet the performance requirements for general use. Assessments conducted by engineers and construction experts prior to the 2010 earthquake concluded that Type I Portland cement was used exclusively for all concrete structural elements on the Republic of Haiti, including hollow concrete blocks and columns (Lang, 2011).

It is understood that in some Haitian cement mixtures, the proportion of cement is elevated which can potentially affect the hydration process and thereby the rate at which the concrete hardens. The effect of cement proportion on the compressive strength of the hardened cement product was tested following the minimum 28 days of setting time required for concrete hardening.

3.2 Water-to-Cement Ratio

As the water-to-cement ratio in the concrete mixture increases, the strength of the hardened concrete decreases. Low water-to-cement ratios are preferred in order to maximise the concrete strength whilst still maintaining workable cement mixtures for use in construction (Cement Concretes and Aggregates Australia, 2010).

3.3 Aggregate Type and Size

Aggregate materials make up approximately 75 percent of the whole concrete mix and providing the requisite strength of the final concrete product (Mamlouk and Zaniewski, 2017). The composition, shape and sizes of aggregate material included in the cement mixtures influences the resulting strength of the hardened concrete (Siregar, et. al., (2017). Ideal aggregate composition includes both coarse and fine aggregate comprising of strong and hard materials (Cement Concretes and Aggregates Australia, 2010). The aggregate should be clean to maximise the bond between aggregate and cement-water paste and graded into a range of sizes to enable a dense and strong structure. Rounded aggregates typically give a more workable mix whilst angular aggregates make a less workable but can increase the strength of the final product (Cement Concretes and Aggregates Australia, 2010).

Haitian derived concrete can include unwashed and poorly graded rounded gravel and sand collected from beaches which may in turn may lower the compressive strength of concrete. (Chang et al., 2013; Lang and Marshall, 2011). In the most populated city region, Port-au-Prince, one and two-story residential structures are constructed using reinforced concrete frames with infilled hollow concrete blocks (Paultre et al., 2013). The inclusion of aggregates harvested from the sea environment can cause corrosion of the surrounding steel reinforcement.

3.4 Addition of Admixtures

Chemical admixtures can be added to a cement mix to perform specific functions such as reducing mixture segregation and accelerating the rate of strength (Musbah, et al., 2019, Mamlouk and Zaniewski, 2017). Admixtures such as water reducers and superplasticisers can be used to increase workability whilst reducing the water-to-cement ratio (W/C) (Medina, et al., 2015 and Corinaldesi, et al., 2001). Admixtures can also be used to improve the durability and strength characteristics of a given concrete mixture (Medina et al., 2015, Corinaldesi et al., 2001).

The Haitian contractor engaged in this research work hypothesised that the addition of admixtures in the Haitian cement production negatively impacts the concrete compressive strength by increasing the required curing time from a typical 28 days to approximately 56 days. The work conducted as part of this research project therefore included testing of this hypothesis.

3.5 Concrete Application and Handling

Compacting the concrete during the setting process removes the entrapped air from the concrete allowing it to form a dense structure. Curing the concrete by keeping it continuously damp/moist for long periods allows the concrete to reach maximum strength and increases its durability.

It is common for concrete to remain uncured in Haiti, even on major projects. This is often due to lack of resources, means and/or lack of knowledge in appropriate concrete application. The effect of curing was tested as part of this research project by designating samples of concrete to be left uncured, exposed only to the natural elements (sun, air, and rain) from the time of mixing until final setting and testing.

Removal of concrete formwork is normally carried out only after the time when concrete has gained sufficient strength, at least twice the stress to which the concrete may be subjected to when the formworks are removed. Generally, the American Concrete Institute (ACI) recommends the removal of formwork 7 days for Type I cement. Although the 28 days is the most accepted age (days) by the construction industry that concrete takes to cure and reach its ultimate strength (Hasan and Kabir, 2013). In order to test the effect of admixtures on curing times the research work included testing of mixtures at varying time spans (3, 7, 14, 28 and 56 days) with and without curing.

4 EXPERIMENTAL DESIGN AND MATERIALS

4.1 Concrete Test Sample Preparation

Two (2) concrete mixture compositions were provided by the Haitian general contractor for testing for this research project, these two compositions have different 28-day compressive strength test results of 24.1 MPa (3,500 psi) and 27.6 MPa (4,000 psi) respectively. For ease of understanding, these two mixture compositions will be referred to as the "24.1 MPa" and "27.6 MPa", respectively.

The 27.6 MPa mixture is a typical mixture commonly used in construction (especially in business construction) in the Republic of Haiti. Two batch types of mixture were prepared for testing – a batch consisting of the Haitian derived cement and a batch consisting of the US-derived cement.

In addition to the 27.6 MPa, batches of the 24.1 MPa mixture were developed for testing consisting of both Haitian-derived and U.S.-derived cement. The characteristics of which can be seen in Table 2 of Section 4.3. The composition of each of the two mixtures is described in more detail in Section 4.3.

Admixture was added to a subset of both the 27.6 MPa and 24.1 MPa mixtures to allow for testing of the effect of the addition of admixtures. Testing cylinder samples of all the mixtures were made in accordance with the ASTM C-192 standard to facilitate compressive strength testing of all test samples produced.

4.2 Materials

Two cement types were tested in this study: Haitian cement Type I - general use, and U.S. Portland cement Type I/II - general and moderate sulfate resistant use (Figure 1).

Five (5) bags of Type 1 cement manufactured by CINA were transported from Haiti to be tested as part of this research project. The U.S-derived cement was produced by Titan America. The cement produced by Titan America is designated as a Type I/II (general and moderate sulfate-resistant use) and meets the requirements of the ASTM C150 Standard Specification for Portland Cement. As per the Haitian derived cement, the Titan America cement can

Figure 1: *Photographs of cement used on this project; Left Haiti Cement and Right US Cement*

used for general use in most concrete construction jobs. Upon visual inspection of both cements, there was no apparent difference noted. Both cements were fine and appeared to contain a similar grain size distribution. The US-derived cement appeared darker (greyer) in colour.

Potable drinking water was added to all the concrete mixtures prepared. Potable or fresh water (i.e. containing less than 1,000 mg/L of dissolved solids) should always be employed in the production of concrete to enable it attain maximum compressive strength over time (Obi, 2016).

The admixture added to all concrete mix samples was added at a rate of approximately 780 mL/100 kg of mixture (12 fl oz/100 lb) for both concrete mixes. This dosage is appropriate for high performance and for producing self-consolidating concrete mixtures. The admixture purchased for inclusion in the Haitian concrete samples was PolyHeed 997 as manufactured by BASF Construction Chemicals. Based on the information presented in the datasheet, PolyHeed 997 admixture is a patented multi-component, non-chloride, mid-range water reducing admixture. Due to issues with corruption at the governmental level in the Republic of Haiti, the research team questioned the quality of the admixtures manufactured in the Republic of Haiti.

The Haitian general contractor provided two concrete mixture compositions for testing. Each mixture contained

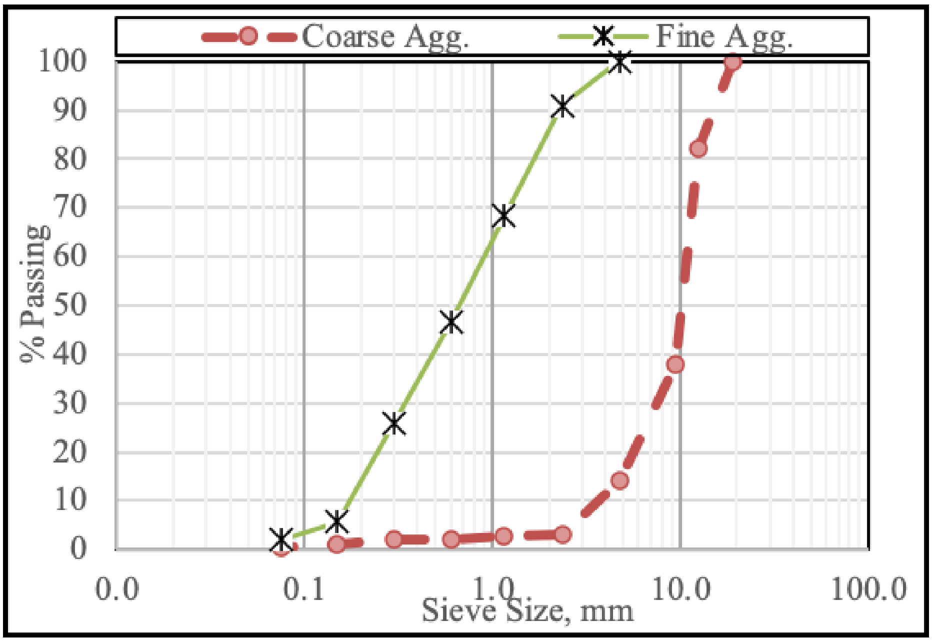

Figure 2: *Gradations of coarse and fine aggregates*

Table 1: Physical and mechanical properties of the aggregate used in this research project

Parameter	Type of Aggregate	
	No. 57 Stone (Coarse Aggregate)	**131 – Screening (Fine Aggregate)**
Maximum size, mm	19	N/A
Fineness modulus	N/A	2.60
Passing No. 200 sieve, %	0.50	2.02
Bulk specific gravity	2.400	2.422
Absorption	5.5%	4.3%
Maximum Dry Density (kg/m^3)	1,557.0	N/A
Los Angeles Abrasion	36.0	N/A

a coarse aggregate composed of medium sized gravel ranging from 6 mm to 25 mm and fine aggregate composed of washed sand. Haiti has deposits of volcanic, silica, and limestone aggregate (Hadden, R and Minson, 2010). The coarse aggregate and fine aggregate commonly used in Haiti was not available for this research project.

Haitian limestone was substituted with Southwest Florida (USA) derived limestone aggregate for this study. Likewise, the coarse aggregate was substituted with No. 57 stone and fine aggregate was substituted with No. 131 – screening fine aggregate. These aggregates have been approved by the Florida Department of Transportation (FDOT). These two types of aggregates are widely, most commonly used aggregates in concrete mixtures in the State of Florida.

Grain size distribution, also known as sieve analysis (gradation), is used to determine aggregate particle size distribution. Figure 2 represents the average grain size distribution on a semi-log scale for the US-derived aggregate substitutes utilised in this research. All sieve analysis tests were performed according to the AASHTO T 27 and ASTM C 136 standard testing procedures. Physical and mechanical tests performed on these aggregate substitutes are presented in Table 1.

Both coarse and fine aggregates were found to be dense and absorptive. The average specific gravity was 2.400 and 2.422 for the coarse and fine aggregate respectively. The absorption was 5.5% and 4.3% for the coarse and fine aggregate, respectively. These values were within typical range values for limestone aggregate. The coarse aggregate was denoted as tough and has a high resistance to crushing and degradation with an LA Abrasion value of 36.0. The maximum particle size for the coarse aggregate 19 mm. Both the coarse and fine aggregates are believed to be superior in quality as compared to the typical aggregates found in concrete production in Haiti. The high quality of the US-derived aggregate mixtures may be due to the presence of quality control procedures during aggregate production.

4.3 Concrete Mixture Composition

Two (2) concrete mixture compositions were provided by the Haitian general contractor for testing for this research project. The 28-day target compressive strength of these mixes was 24.1 MPa (3,500 psi) and 27.6 MPa (4,000 psi), respectively. Despite the use of substitute aggregates for the Haitian mixture samples, effort was made to balance the weight of the materials of similar values of those from the mixes in Haiti. The mixes were originally designed to contain the following constituents: No. 57 limestone as coarse aggregate, No. 131 screenings as fine aggregate, and admixture. The mixture compositions were designed following the weight and absolute volume methods (Mamlouk and Zaniewski, 2017).

The total weight of the concrete mixtures inclusive of all its constituents (i.e. aggregates, water, cement, and admixture) are presented in Table 2. The design slump for these mixes was selected as 125 ± 25 mm, non-air-entrained concrete, and nominal maximum coarse aggregate size of 12.5 mm. The variation in the slump was due to variability of the equipment and operator during mixing. As can be seen in Table 2, the slump in the Haitian mixtures was reported to be lower or equal to the corresponding US-derived mixtures.

In this study, a comparative approach between the Haitian mixtures versus the US-derived mixtures was used to

Table 2. Composition of concrete mixtures

Mix Name[a]	Cement kg/m³	Water kg/m³	Slump[b] mm	No. 57 kg/m³	131-Scr. kg/m³	Adm mL/m³	W/C
H-27.6-Adm-UC	434	296	200	701	980	2,591	0.68
US-27.6-Adm-UC	434	263	200	701	980	2,591	0.61
H-27.6-Adm-C	434	286	129	701	980	2,591	0.66
US-27.6-Adm-C	434	286	220	701	980	2,591	0.66
H-27.6 -C	434	286	81	701	980		0.66
US-27.6 -C	434	286	113	701	980		0.66
H-24.1-Adm-C	380	239	81	933	693	2,266	0.63
US-24.1-Adm-C	380	275	125	933	693	2,266	0.72
H-24.1-C	380	258	150	933	693		0.68
US-24.1-C	380	261	156	933	693		0.69
H-27.6-Adm-UC-15%	499	269	200	701	980	2,980	0.54
US-27.6-Adm-UC-15%	499	259	119	701	980	2,980	0.52
H-27.6-Adm-UC-30%	564	288	88	701	980	3,368	0.51
US-27.6-Adm-UC-30%	564	254	50	701	980	3,368	0.45
H-27.6-Adm-UC-50%	651	319	106	701	980	3,887	0.49
US-27.6-Adm-UC-50%	651	306	106	701	980	3,887	0.47
H-24.1-Adm-C-15%	437	223	100	933	693	2,606	0.51
US-24.1-Adm-C-15%	437	267	150	933	693	2,606	0.61
H-24.1-Adm-C-30%	494	222	94	933	693	2,946	0.45
US-24.1-Adm-C-30%	494	247	100	933	693	2,946	0.50
H-24.1-Adm-C-50%	570	279	113	933	693	3,399	0.49
US-24.1-Adm-C-50%	570	296	115	933	693	3,399	0.52
H-27.6-Adm-C-15%	499	240	88	701	980	2,980	0.48
US-27.6-Adm-C-15%	499	274	106	701	980	2,980	0.55
H-27.6-Adm-C-30%	564	254	106	701	980	3,368	0.45
US-27.6-Adm-C-30%	564	282	106	701	980	3,368	0.50
H-27.6-Adm-C-50%	651	286	113	701	980	3,887	0.44
US-27.6-Adm-C-50%	651	293	119	701	980	3,887	0.45

Notes:
[a] H-27.6-Adm-UC = H → Haiti Mix; 27.6 → 27.6 MPa; Adm → Admixture; UC → Un-Cured
US-24.1-Adm-C = US → US Mix; 24.1 → 24.1 MPa; C → Cured;
15% → 15% of additional cement; 30% → 30%of additional cement; 50% → 50% of additional cement
[b] N/A → Not available

assess performance. The only difference between the mixtures produced for the research study versus that produced by the Haitian general contractor was the amount of water added to each mixture. The amount of water added to the text mixtures produced for this research study was higher producing an average water-to-cement ratio of 0.65 as opposed to the water-to-cement ratio of 0.40 adopted by the Haitian general contractor at a slump of 75 mm. A water-to-cement ratio 0.65 is considered high, however research shows that mixtures with higher water-to-cement ratios can still achieve 27.6 MPa (4,000 psi) by 7 days of setting (LeBow, 2018; Wassermann, et al., 2009).

4.4 Testing Methodology

The hypothesis tested as part of this research work was the assumption that the Haitian and US-derived cement, being similar in quality, would produce comparable performance results when subject to a battery of testing. The 24.1 MPa and 27.6 MPa samples were subject to compressive strength testing to understand the following:

- The effect of cement proportion on the compressive strength of the final hardened concrete product - test samples of the 24.1 MPa and 27.6 MPa Haitian-derived and U.S.-derived mixtures were subject to increasing concentration of cement content ranging from 15 to 50%.
- The effect of curing on the compressive strength of final concrete product test samples - the 24.1 MPa and 27.6 MPa Haitian-derived and U.S.-derived mixtures were cured according to ASTM C-192. All the specimens were immersed in a water bath maintained at temperature 25^{o}C) until the nominated testing period.
- The effect of air curing on the compressive strength of the mixtures - the 27.6 MPa test samples were left outside subject to natural weather conditions over the month of May to September. The temperature in Fort Myers, Florida ranged from 20^{o}C (68^{o}F) to 34^{o}C (93.2^{o}F) which are similar temperatures to

Table 3: *Testing matrix*

Test sample labels	Description	Purpose
27.6 -C	• 27.6 MPa • Cured	Understand the effect of curing on for a 27.6 MPa sample
27.6-Adm-UC	• 27.6 MPa • Air cured • Containing Admixture	Understand the effect of addition of admixture to uncured sample
27.6-Adm -UC- 15% 27.6-Adm -UC - 30% 27.6-Adm - UC - 50%	• 27.6 MPa • Air cured • Containing Admixture • Varying cement quantities	Understand the effect of addition of admixture to an uncured 27.6 MPa sample at varying cement proportions
27.6-Adm-C-15% 27.6-Adm-C-30% 27.6-Adm-C-50%	• 27.6 MPa • Cured • Containing Admixture • Varying cement quantities	Understand the effect of the addition of admixture in the curing process for cement at varying cement proportions
24.1-C	• 24.1 MPa • Cured	Understand the effect of curing on for a 24.1 MPa sample
24.1-Adm-C-15% 24.1-Adm-C-30% 24.1-Adm-C-50%	• 24.1 MPa • Cured • Containing Admixture	Understand the effect of addition of admixture to an uncured 24.1 MPa sample at varying cement proportions

that experienced in Port-au-Prince, Haiti during the same time of year (Crawford-Adiletta, 2019, NOAA, 2020) with the exception of humidity. The average humidity in Fort Myers was 90% in comparison to 50% in the Republic of Haiti.

- The effect of the addition of admixtures on the compressive strength of the final hardened concrete product, and the effect of the addition of admixture have on the curing time required to achieve the required compressive strength, batches of 24.1 MPa and 27.6 MPa Haitian-derived and U.S.-derived mixtures both containing admixture and not containing admixture were subject to testing.

A summary of the testing samples produced as part of this research study are summarised in Table 3.

5 RESULTS AND DISCUSSIONS

5.1 Un-cured (Air-cured) Treatment

The 14, 28, and 56 days' compressive strength tests for the uncured Haitian-derived cement mixtures and the uncured US-derived cement mixtures are presented in Figure 3.

As can be seen in Figure 3, the Haitian-derived cement mixture increased in strength by 39% between the 28 day to 56 day setting period. The compressive strength of the Haitian mixture however never reached the target strength even at a setting period of 56 days. The highest compressive strength recorded for this mixture was 19.6 MPa at 56 days setting time. At 28 days, the compressive strength for the Haiti mix was 42% lower than the target strength of 27.6 MPa. The US-derived mixture reached the target strength of 27.6 MPa at approximately 14 days. No significant increase in strength was noted on the U.S.-derived mixture over the setting time period.

From the results shown in Figure 3, it can be inferred that the hydration reaction for the US-derived cement mixture appears to have slowed down significantly after day 14 of setting. The U.S.-derived cement mixture compressive strength at 28 days was recorded at 30.5 MPa (11% higher than the target strength of 27.6 MPa). The critical point to note is that, on average, the compressive strength of the U.S.-derived mixtures was 44% stronger than the Haitian-derived mixtures.

5.2 Effect of Cement Content on Air-Cured Samples

A sensitivity analysis was conducted by varying the amount of cement content in both the Haitian-derived concrete mixtures and U.S.-derived concrete mixtures. The purposed of this sensitivity analysis was to evaluate the effect of increasing the cement content on the compressive strength of the final concrete product. Compressive strength is understood to increase as the proportion of cement in the mixture increases.

All Haitian-derived and US-derived samples tested were uncured and contained admixture. The cement content in each sample was increased by 15%, 30%, and 50% by mass, relative to the total mass of the cement content in the original mixture composition. All other parameters,

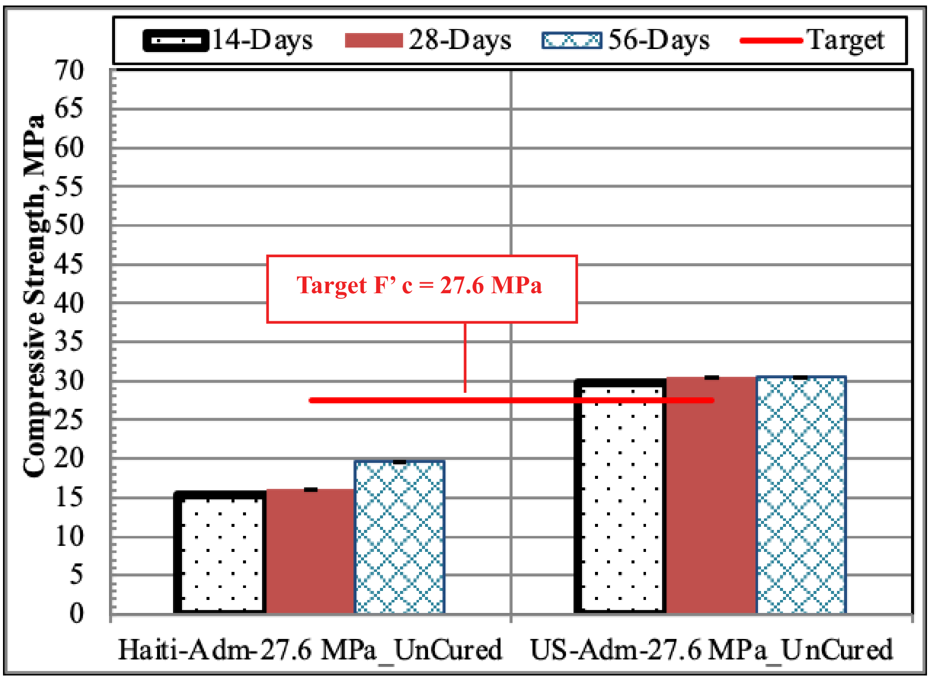

Figure 3: Compressive strength results for the 27.6 MPa using both Haiti cement with admixture and US cement with admixture (Un-cured mixes).

including coarse and fine aggregates, were kept constant (Table 2). The amount of water was adjusted to maintain the original slump of 125 ± 25 mm. The compressive strength is presented in Figure 4 for the Haitian-derived and US-derived mixtures, respectively

As seen in Figure 4, an increase in the cement content of both the U.S.-derived and Haitian-derived mixtures resulted in an increase in the compressive strength. A greater increase in compressive strength was observed for the Haitian-derived mixtures in comparison to the U.S.-derived mixtures. On average, the compressive strength of the Haitian-derived mixtures increased by 34%, 44%, and 36% as the cement content increased by 15%, 30%, and 50%, respectively. For the U.S.-derived mixtures, the increase in compressive strength was 17%, 30%, and 33% for the same increase in cement content. When the cement content was increased from 30% to 50% in the Haitian-derived mixture, no apparent increase in compressive strength was observed.

Although both the Haitian-derived and U.S.-derived mixtures increased in compressive strength over the setting period as the cement content increased, the change in the compressive strength between days 28 to 56 was marginal for both the Haitian-derived and U.S.-derived mixtures (Figure 4). As can be seen in Figure 4, the compressive strength for the Haitian-derived mixtures increased by 10% from day 14 to day 28 and another 6% from day 28 to day 56. The compressive strength of the U.S.-derived mixture did not increase as much as compared to the Haitian-derived mixture over the setting period. The increase in compressive strength was approximately 4% and 2% for the U.S.-derived mixture.

Although a noticeable increase in compressive strength was observed in the Haitian-derived mixture, it did not reach the target compressive strength value of 27.6 MPa, even at the highest cement content and/or at 56 days setting time. A maximum compressive strength of 26.5 MPa was noted at 28 days setting time when the cement content was increased to 30%. This value is still 4% lower than the target strength of 27.6 MPa (Figure 4). As the test sample dimensions were the standard size of 100 mm by 200 mm specimens, a five (5) percent reduction in strength should be expected should the standard 150 mm by 300 mm (6″×12″) specimens be used instead (Jihad Hamad, 2017).

In addition, the aggregates used in the mixtures were superior to the typical aggregates used in concrete production in Haiti. Better quality aggregate is expected to produce higher compressive strength in the final hardened concrete. Furthermore, the quality control used to produce the mixtures was well maintained; this is not known to be the standard practice in construction projects on the Republic of Haiti. The highest compressive strength of the U.S.-derived mixture was 44.4 MPa (68% higher than the Haitian-derived mixture). The maximum compressive strength was observed in the samples containing 50% cement content on the 56th day of setting.

5.3 Effect of Curing

An analysis was conducted to determine the effect of curing on the concrete mixtures. Curing plays an important role

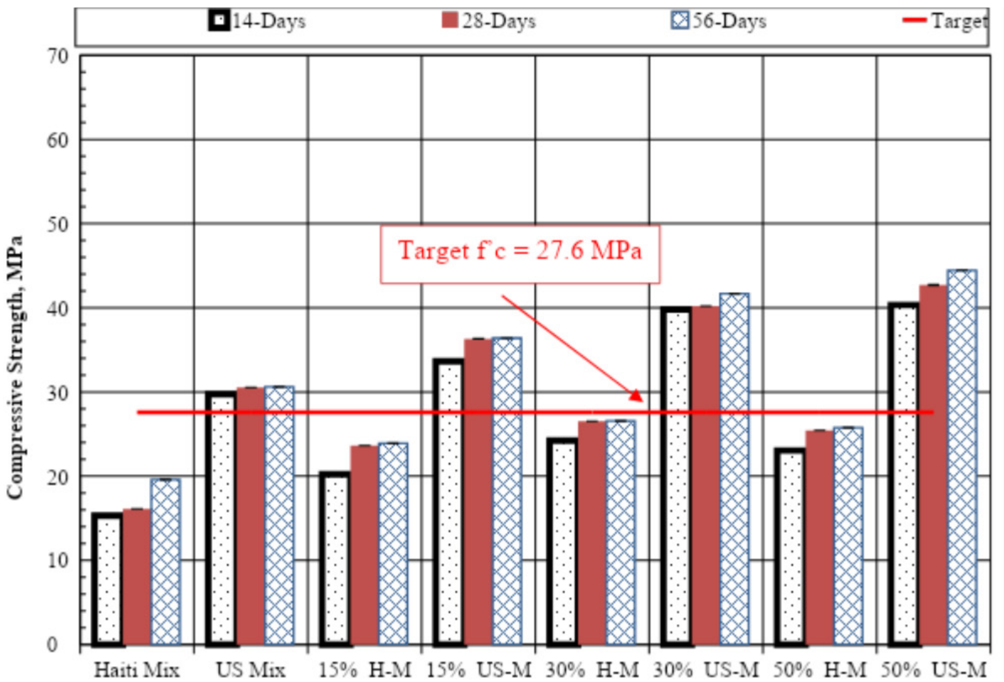

Figure 4. Sensitivity of 27.6 MPa Haiti mix with admixture and 27.6 MPa U.S.-derived mixture with admixture – (Un-cured mixes).

on strength development and durability of concrete. The strength of appropriately cured (i.e. continually moistened) concrete is normally three times greater than the strength of air-cured concrete (Mamlouk, M and Zaniewski, 2017). Test samples of the 27.6 MPa Haitian-derived and U.S.-derived mixtures were cured according to ASTM C-192. All the specimens were immersed in a water bath maintained at temperature 25°C) until the testing period. The compressive strength of the samples at days 14, 28, and 56 days are presented in Figure 5. A significant increase in compressive strength can be seen for both the cured Haitian-derived and U.S.-derived mixtures in comparison to the uncured samples.

The compressive strength of the Haitian-derived mixture was doubled when subject to curing. Similarly, the compressive strength of the U.S.-derived mixtures was increased by 77%. This increase in compressive strength is

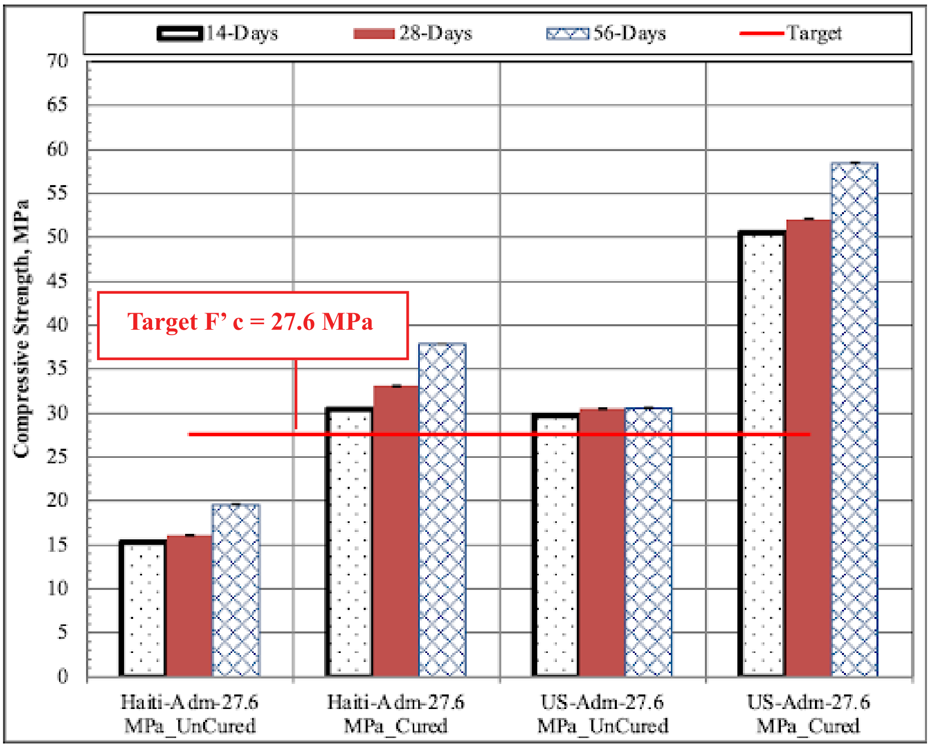

Figure 5. Effect of curing on both the 27.6 MPa Haitian-derived mixtures and 27.6 MPa U.S.-derived mixtures.

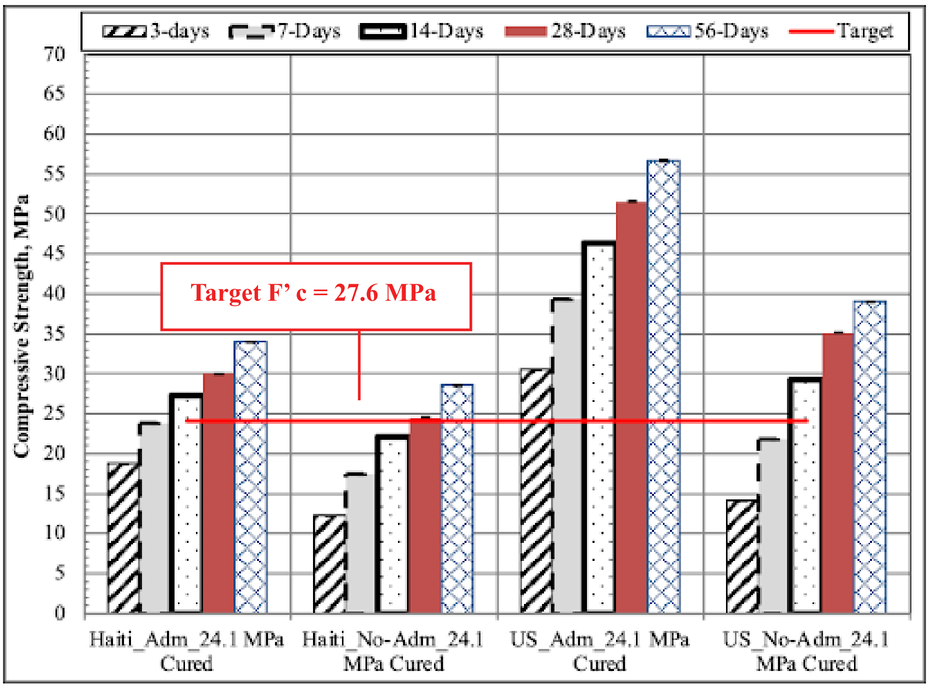

Figure 6. Effect of admixture on the compressive strength of the 24.1 MPa mixtures

due to the continual moistening of the concrete mixture, allow the sample to undergo the hydration reaction continuously to develop and increase the bond between the aggregate and the cement-water paste. The 28 day compressive strength test result for the Haitian-derived mixtures was 33.1 MPa which is 20% higher than the target strength of 27.6 MPa.

Although the increase in strength observed in the Haitian-derived mixture was encouraging, the U.S.-derived mixture was still seen to outperformed the Haitian-derived mixture. The compressive strength of the un-cured U.S.-derived mixture was comparable to that of the cured Haitian-derived. Furthermore, when the U.S.-derived mixture was cured, the maximum compressive strength was reported to be 58.6 MPa, 55% higher than the Haitian-derived mixture.

5.4 Effect of Addition of Admixtures on Compressive Strength

The Haitian contractor hypothesised that the admixture typically used in construction practice in Republic of Haiti increased the total minimum curing time required for concrete work, presumable by decreasing the rate of hydration experienced during the settling time. To test this hypothesis, an analysis was conducted to test the effect of the addition of admixture to the concrete mixtures on the compressive strength of the concrete.

Based on the data presented above, it is evident that the addition of admixture to U.S.-derived mixtures does not pose negative effects on the compressive strength of the concrete product. Both the 24.1 MPa and 27.6 MPa mixes were produced for the Haitian-derived and U.S.-derived cement mixtures, with the exclusion of the admixture. The compressive strength for the 24.1 MPa and 27.6 MPa mixtures were tested on days 3, 7, 14, 28, and 56 of the setting period. The results of these tests are presented in Figure 6 and Figure 7, respectively.

The admixture had significant effect on the compressive strength of all the samples tested. All the sample mixtures tested gained strength over the setting period where the admixture was present. For the 24.1 MPa cured mixtures, the 28-day compressive strength was 30.1 MPa (Haitian-derived, with admixture), 24.6 MPa (Haitian-derived, no admixture), 51.6 MPa (U.S.-derived, with admixture), and 35.1 MPa (U.S.-derived, no admixture), respectively (Figure 6). Where the admixture was omitted, the 28-day compress strength of the cured Haitian-derived mixture decreased by 18% with the U.S.-derived mixture decreasing by 32%.

For the 27.6 MPa cured mixes the compressive strength of the Haitian-derived mixture decreased by 11%. Similarly, for the 21.4 MPa mixes, an increase in strength was observed for the 27.6 MPa mixtures where admixture was included. On average, a 22% increase in compressive strength was observed in the Haitian-derived mixture where admixture was included as compared to the Haitian-derived mixture where the admixture was omitted. The increase in compressed strength observed in the U.S.-derived mixture was approximately 5%.

Another benefit of the addition of admixtures is the time taken for the concrete to reach an adequate strength. The

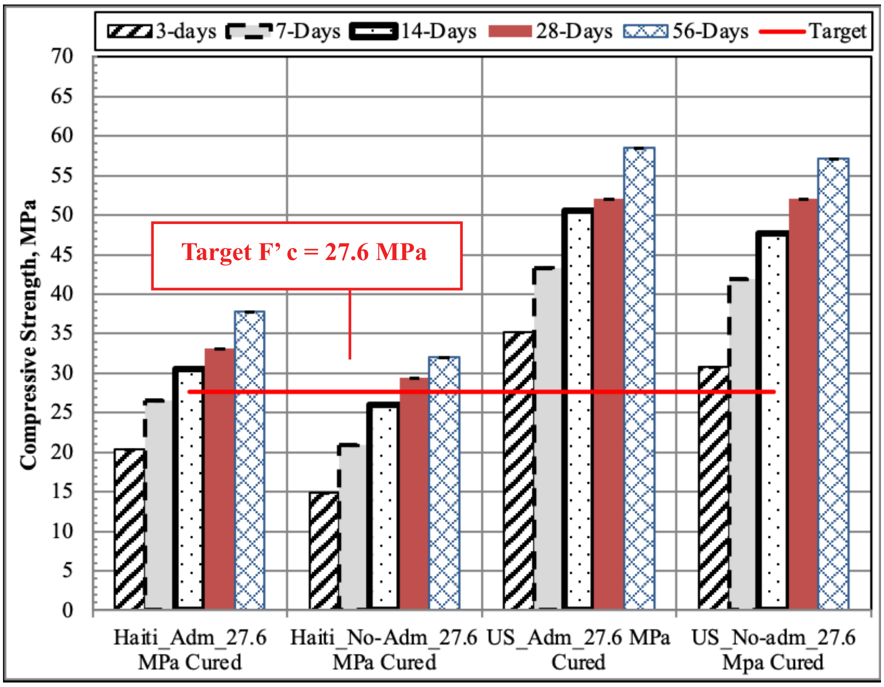

Figure 7. Effect of admixture on the compressive strength of the 27.6 MPa mixtures

removal of the concrete formwork is normally carried out only after the time when concrete has gained sufficient strength. As a rule of thumb, 75% of the ultimate strength of a good quality concrete is reached in 7 days. Using this rule, when admixture was used, formworks could be removed on the third (3rd) day after pouring for the Haitian-derived mixtures; this increased to approximately 14 days of setting time for mixtures where admixture was not included. The addition of admixture and time taken for concrete setting are important financial considerations to take into account for the total cost of a project.

5.5 Effect of Cement Content on Cured Samples

A sensitivity analysis was conducted by varying the amount of cement content in both the Haitian-derived concrete mixtures and U.S.-derived concrete mixtures. The purpose of this sensitivity analysis was to evaluate the effect of increasing the cement content on the compressive strength of the final concrete product assuming the concrete is appropriately cured. Compressive strength is understood to increase as the proportion of cement in the mixture increases.

The cement content in each sample was increased by 15%, 30%, and 50% by mass, relative to the total mass of the cement content in the original mixture composition for both the 24.1 MPa and 27.6 MPa mixtures. All samples were cured until testing. Admixture was included in both the Haitian-derived and U.S.-derived mixtures.

The compressive strength test results for all samples are presented in Table 4. For the 24.1 MPa and 27.6 MPa mixtures, respectively. Table 4 contains the results for compressive strength for all the mixtures tested as part of this study. This provides a broader comparison of the compressive strength for all mixtures tested across the 14, 28, and 56 day setting periods.

Similar to the results of the uncured samples presented in Section 5.3, increasing the cement content of the mixtures has a significant effect on the compressive strength of the mixtures where the cylinders were continually cured prior to testing. On average, the compressive strength for the Haitian-derived 21.4 MPa mixture increased to 14% from day 14 to day 28. An additional increase of 14% was observed from day 28 to day 56. For the U.S.-derived mixture, the increase observed was approximately 12% and 11%, respectively. The maximum compressive strength of the 24.1 MPa Haitian-derived mix was 45.9 MPa on day 56 of the setting periods where the cement content was 50%. A similar increase in compressive strength was observed for the 27.6 MPa mixtures.

A more notable increase (18%) in compressive strength was observed when the cement content in the 24.1 MPa Haitian-derived mixture increased by 30%. For the 27.6 MPa Haitian-derived mixture, the compressive strength increased to 25% when the cement content was increased by 15%. An additional 14% increase in compressive strength was noted when the cement content of the mixture was increased by 50%. The maximum compressive strength of the 27.6 MPa Haitian-derived mixture was 54.4 MPa on day 56 of the setting period where the cement content was 50%.

The U.S.-derived mixtures out-performed the Haitian-derived mixtures. On average, the U.S.-derived mixtures produced a 40% greater compressive strength as compared to the Haitian-derived mixtures. The maximum compressive strength of the 27.6 MPa U.S.-derived mixtures was 66.2 MPa where cement content was increased to 30%.

6 CONCLUSION AND RECOMMENDATIONS

The main objective of this project was to evaluate the quality of the cement and admixture commonly used in concrete production in Haiti. CINA cement and BASF admixtures were obtained from a construction contractor in Republic of Haiti for the purposes of this study. Extensive data was produced. Based on the analysis conducted, the following conclusions can be drawn:

- A literature review was conducted to understand the current state of the construction practice in Haiti. The country is prone to very powerful earthquakes and hurricanes which can result in damage of poorly constructed infrastructure leading to high loss of life. The 28-day compressive strength tests of concrete in Haiti showed that the typical ranges of compressive strength ranged from 2.8 MPa (410 psi) to 8.7 MPa (1,260 psi). This is much lower than the minimum specified concrete strength for residential building in the United States (US) is 20.7 MPa (3,000 psi) and may be a cause of concern for the robustness of infrastructure in the Republic of Haiti that is subject to extreme weather conditions.
- The results obtained from this work reject the hypothesis that the Haitian manufactured cement tested produced comparable results to U.S. manufactured cement. The cement used in construction in the Republic of Haiti can be considered inferior quality material in comparison to U.S. manufactured cement. The average 28-day compressive strength of the concrete mixes produced with cement commonly used in construction practice in the Republic of Haiti was 56% weaker compared to the concrete mixes produced with cement manufactured in the U.S.

Table 4: Compressive strength of all the mixtures tested in the research study

Mixture	**Compressive Strength (MPa)**		
Name[a]	**14-Days**	**28-Days**	**56-Days**
H-27.6-Adm-UC	15.3	16.1	19.6
US-27.6-Adm-UC	29.8	30.5	30.6
H-27.6-Adm-C	30.5	33.1	37.8
US-27.6-Adm-C	50.5	52.1	58.5
H-27.6 -C	26.1	29.4	32.1
US-27.6 -C	47.7	52.1	57.1
H-24.1-Adm-C	27.2	30.1	34.0
US-24.1-Adm-C	46.4	51.6	56.7
H-24.1-C	22.1	24.6	28.6
US-24.1-C	29.3	35.1	39.0
H-27.6-Adm-UC-15%	20.2	23.6	23.9
US-27.6-Adm-UC-15%	33.6	36.3	36.4
H-27.6-Adm-UC-30%	24.2	26.5	26.5
US-27.6-Adm-UC-30%	39.8	40.2	41.7
H-27.6-Adm-UC-50%	23.1	25.4	25.7
US-27.6-Adm-UC-50%	40.3	42.7	44.4
H-24.1-Adm-C-15%	28.2	35.9	39.1
US-24.1-Adm-C-15%	46.5	53.3	59.3
H-24.1-Adm-C-30%	32.8	35.1	40.6
US-24.1-Adm-C-30%	55.1	60.1	66.8
H-24.1-Adm-C-50%	33.9	38.8	45.9
US-24.1-Adm-C-50%	52.2	58.5	65.3
H-27.6-Adm-C-15%	38.0	42.2	47.1
US-27.6-Adm-C-15%	51.3	55.7	56.6
H-27.6-Adm-C-30%	39.6	44.0	49.8
US-27.6-Adm-C-30%	56.6	64.7	66.2
H-27.6-Adm-C-50%	45.9	50.6	54.4
US-27.6-Adm-C-50%	55.5	62.1	62.7

Table Notes:
[a] H-27.6-Adm-UC = H → Haiti Mix; 27.6 → 27.6 MPa; Adm → Admixture; UC → Un-Cured
US-24.1-Adm-C = US → US Mix; 24.1 → 24.1 MPa; C → Cured;
15% → 15% of additional cement; 30% → 30% of additional cement; 50% → 50% of additional cement

- Curing had a significant effect on the compressive stress of all samples tested, both Haitian and U.S. derived cement mixtures. When the specimens were not cured, the Haitian mixes did not reach the target compressive strength of 27.6 MPa. This observation was noticed even when the cement content in the original design was increased by 50% and/or the mixtures were tested at 56 days.

- The admixture used in the construction practice in Haiti was not shown to have any negative effects on the Haitian-derived concrete mixes. However, the admixture should not be treated as a retarder as originally assumed by the contractor in Haiti. When the admixture was added, the mixtures, especially those made with U.S.-derived cement, reached the target strength as early as 7 days. No significant increase in compressive strength was noted from 28 days to 56 days.

- According to the Haitian contractor, it was not feasible to import cement to the Republic of Haiti. Therefore, in order to produce hardened concrete products of suitable compressive strength, concrete producers in Haiti should consider increasing the cement content of existing concrete mixtures to at least 30%. Doing so, will increase the cost of construction, however maintaining appropriate concrete products in construction will enable the construction of robust buildings that are prone to the effects of natural disasters like hurricanes and earthquakes. Other alternative methods such as the use of different admixture and curing techniques need to be evaluated.

- The mixtures used in this research study were sensitive to the amount of water added. Although high quality control was set in place during mixing, high variation in slump was observed. This was due to variation in equipment and operator skill. The general rule is the higher the slump the lower the compressive strength. However, the variation in slump did not undermined the findings of this research. At all the times, the slump in the Haitian-derived mixtures were lower or equal to the corresponding U.S.-derived mixtures.

- The research work conducted was limited to the testing of one cement type and one admixture type manufactured in the Republic of Haiti. Continued research in this area is encouraged. Work is in progress to evaluate the effect of various cements and admixtures in differing proportions. In addition, effort will be made to include typical aggregates used in concrete product in the Republic of Haiti. It is also recommended to verify if Haitian cement can be classified as Portland Cement.

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