ECONOMIC VIABILITY AND COMPRESSIVE STRENGTH OF ROLLER COMPACTED CONCRETE PAVEMENT (RCCP)

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ABSTRACT

The pavement industry is one of the areas where sustainability must be practiced. Roller Compacted Concrete (RCC), a zero-slump concrete, is a new engineering material here in the Philippines having the same basic ingredients as conventional concrete but of different mix proportions. It is constructed without forms and reinforcement. Fresh RCC mix is dry enough to support a roller while being compacted and wet enough to accommodate complete hydration of cementitious materials. The foremost objective of this study is to determine the compressive strength of RCC slab when compacted by a 68-kg soil compactor. Soil Compaction Analogy Method (ASTM D-1557) was used in determining the maximum dry density (MDD) and optimum moisture content (OPC). A compaction pattern is observed with 5 passes of the compactor in each direction. Three (3) RCC slabs (0.91 x.70 x.15 m) were constructed, and water cured for 3 days, 14 days, and 28 days respectively. Properties of crushed ¾" aggregates, rounded ½" aggregates, natural sand, and cementitious materials (Portland Type 1 and Fly ash) were all tested prior to using it in the experiment. A total of 18 core samples were extracted from the 3 slabs, six for each slab. The cores were then tested for compressive strength determination following ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Initial results showed that the strength attained by RCC is 32% higher than the designed strength developed by DPWH for the 3-day maturity and 47% higher for the 14-day maturity time. It is recommended that the observation of the maturity of concrete be extensive and to be observed for a longer period of time to evaluate further its characteristics and behavior. Lastly, an in-depth study of the economic viability of RCC pavement as a substitute to Portland cement concrete pavement and a comparison in terms of cement content, construction time, and production unit cost must be conducted.

Keywords: *Roller Compacted Concrete Pavement, Compressive Strength, Vibratory Compaction, Sustainable Pavement, Fly Ash, Concrete Pavement*

INTRODUCTION

The pavement industry is one of the areas where sustainability must be practiced, maintaining a balance between the economic viability and the environmental and social obligations of a particular pavement project (Dam, Taylor, Fick, Gress, VanGeem, Lorenz, 2011). Manufacturing portland cement is a very intensive process and emits a significant amount of CO2 in the environment. But recently, advances in the technology and cement production processes have greatly decreased these impacts. Furthermore, some modern concrete for pavements uses less portland cement per cubic unit compared to the past cement ratio of the same volume, and thus lowering the carbon footprints discharged to the environment (Dam et al., 2011). Roller-Compacted Concrete (RCC) is a new engineering material having the same basic ingredients as the conventional concrete but of different mix proportions. RCC is constructed without forms, dowels, or reinforcing steel bars (Harrington, Abdo, Adaska, & Hazaree, 2010) and has of lesser water-cement ratio compared to conventional concrete.

RCC has many sustainability attributes like the conventional concrete pavements. Low lifecycle economic costs, the ability to incorporate a high amount of recycled and industrial byproduct material (RIBM) into the mix, and high surface reflectivity are few of them. Some of the specific advantages of RCC from a sustainability perspective include low initial cost and rapid construction time compared to both conventionally designed concrete pavements of similar structural capacity. And because of its lower water-cement ratio, the carbon footprint is reduced (Dam, et al., 2011). With these advantages in sustainability, comparing the compressive strength of RCC pavement and conventional Portland Cement Concrete (PCC) pavement can be of great significance in choosing a better pavement to meet the needs of society.

Objectives of the Study

The foremost objective of this study was to determine the compressive strength of Roller-Compacted Concrete. Also, this research study has the following specific objectives:

1. To determine the compressive strength of cored Roller-Compacted Concrete cylinder based on the following duration of curing:
   1.1 3-day Curing
   1.2 14-day Curing
   1.3 28-day Curing
2. To compare the compressive strength of cylinder samples casted in laboratory and cored samples.
3. To compare Roller-Compacted Concrete with the conventional Portland cement concrete pavement (PCCP) for secondary roads designed by Department of Public Works and Highways (DPWH) in terms of cement content and strength.

METHODOLOGY

The experimental research design of RCC mix proportioning using the Soil Compaction Analogy Method, adopted from Guide for Roller-Compacted Concrete Pavements (2010) which includes the following general procedure: determination of the physical properties of materials to be used, choosing well-graded aggregates for combined grading, selection of cementitious materials content, develop a moisture-density curve, determination of the Optimum Moisture Content, casting and curing of samples to measure compressive strength, test cylinders specimens and select required cementitious content, and calculate mixture proportions. After calculating the mix proportions of the materials, construction of the RCC test slab follows, then placing of the RCC in the mold, compacting RCC slab, curing the test slab, and obtaining and testing for compressive strength of the cored samples.

Determination of the Physical Properties of Materials Used

Figure 1

Materials used in the Experiment

In testing the materials, ASTM C-136, C127-01, and ASTM C 128-01 were followed. The tests were conducted in the Material Testing Laboratory of Civil Engineering Department of MSU-IIT. The materials used in the study is shown in Figure 1.

Cementitious materials

Type 1 ordinary portland cement manufactured in Holcim Cement Lugait Plant was used in the experiment. The testing of cement was done in the laboratory of the Holcim Cement. The fly ash used in the experiment was taken from STEAG Power Plant in Villanueva, Misamis Oriental. It was tested in the laboratory of Lafarge Cement located at Kiwalan, Iligan City. XRF Fused Bead test was conducted to test the physical and chemical properties of a 5-kg sample submitted fly ash.

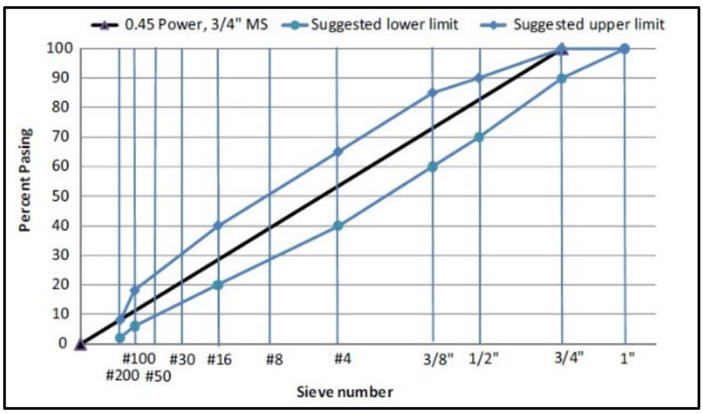
Aggregates

The fine aggregates used in this research are natural sand and pulverized sand. Pulverized sand is natural sand that is pulverized using a ball mill so that it will pass thru a No. 50 sieve mesh.

Two types of coarse aggregates were used in the study, ¾" crushed aggregates and ½" rounded aggregates. Combined aggregates grading requirements of RCC (Harrington, et. al, 2010) are shown in Figure 2.

Figure 2

Recommended RCC Pavement combined aggregate grading limit



Selecting of Cementitious Materials Content

The choice of cementitious materials was based on the compressive or flexural strength specifications of the project, economic considerations, availability of the materials, and production consideration (Harrington et al., 2010). For secondary roads, a compressive strength of 3000 psi and a flexural strength ranging from 600 to 700 psi are already acceptable. This determined strength corresponds to 10 to 17% by mass of dry aggregates (American Concrete Institute [ACI], 2002). 3000 psi was used as a design compressive strength for this study. (Department of Public Works and Highways [DPWH], 2014).

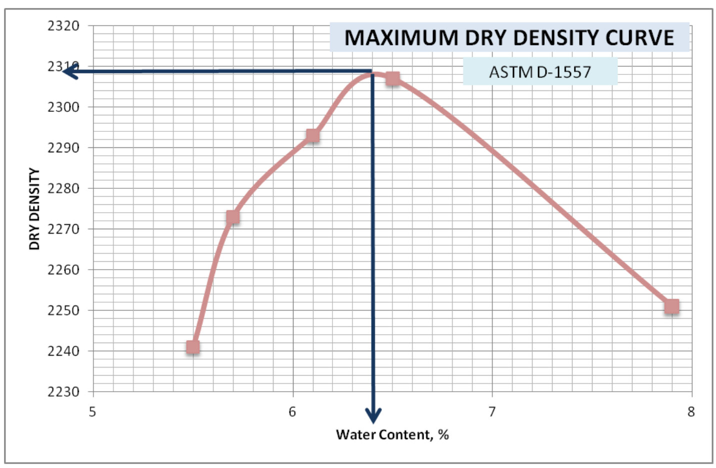
In determining the actual breaking compressive strength of the RCC cylinders, the researcher used two (2) types of mixes. Mix 1 (M1) is composed of natural sand, and ¾" crushed gravel, Type 1 Portland cement and water. Mix 2 (M2) is composed of pulverized sand, natural sand, 1/2" rounded gravel, ¾" crushed gravel, and the cementitious material for M2 was composed of fly ash and Type 1 Portland Cement.

Developing a Moisture-Density Curve

Using the combined aggregate grading and the chosen cementitious material content, ASTM D-1557 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort was performed for the two types of mixes. Sample moisture-density curve as shown below in Figure 3:

Figure 3

Moisture-Density Curve



Casting and Curing of Samples to Measure Compressive Strength

This study used four (4) cementitious contents in making cylindrical samples, specifically, 10%, 12%, 14%, and 16%. Using the obtained Optimum Moisture Content (OMC) from the Maximum Dry Density (MDD) curve, and the four cementitious contents, cylindrical specimens are made using a vibrating hammer following the ASTM C1435 - Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds using a Vibrating Hammer.

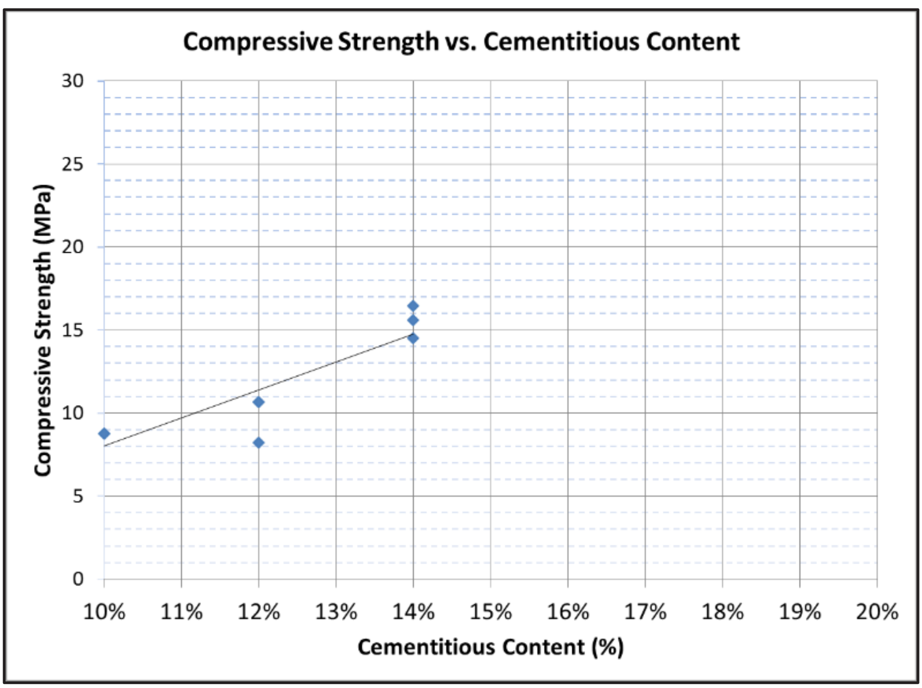
After molding the samples, it was cured by immersing the cylinder samples in a curing tank available in the Civil Engineering Department of MSU-IIT for 28 days for all the cylinders.

Testing for Compressive Strength of the Cylindrical Samples and Select Required Cementitious Content

Cylindrical samples are then tested for compressive strength using a Compressive Testing Machine with a maximum capacity of 2000KN in City Engineering Office located at Pala-o, Iligan City. The test followed the guidelines in ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. The obtained compressive strengths are then plotted in a graph together with its respective cementitious content. Figure 4 is a graph showing compressive strength versus cementitious content. From the plotted graph, a cementitious content was selected to meet the required strength. The required strength is calculated as specified strength plus safety factor.

Figure 4

Compressive Strength of RCC vs. Cementitious Content



Calculate Mixture Proportions

After selecting the cementitious content and the optimum moisture content, a final mix proportion was calculated. Saturated surface-dry (SSD) condition of aggregates should be used in calculating the weight and equivalent volume of the materials (Harrington et al., 2010, p. 40).

Construction of RCC Test Section

For this study, 3 slab molds were constructed, 1 steel mold and 2 wooden molds, respectively. The inner dimension of each slab was 0.97m x 0.71m and a thickness of 0.150m., shown in Figure 5. The construction of RCC slab took place in JJ Horizon Batching Plant, Barinaut, Iligan City.

Figure 5

RCC Slab Molds

Mixing and Placing of the RCC

Using the calculated RCC mix proportion, weighing of the construction materials followed. The mixing RCC mix was done using a one bagger concrete mixer. To accomplish 98-100% compaction, two layers of RCC mix were made. Each layer is 3 inches thick. Immediately after mixing, fresh RCC mix was placed in the mold up to ¾ of the total thickness of the slab to accommodate compaction.

Compacting RCC slab

When the 1st layer of RCC was placed in the mold, internal tamping was performed to the fresh RCC to induced interior vibration, thus minimizing the air voids. Figure 2.9 shows the soil compactor used to compact the fresh RCC. The vibratory soil compactor has a total dead weight of 68 kilograms, an effective compaction area of $0.19m^2$ and a compaction force of 13KN with 5,488 vibrations per minute (VPM) It was borrowed from E.M. Cuerpo Construction Company.

A compaction pattern was followed to secure proper distribution of compaction effort all throughout the slab area (Sarsam, Al-Rawi, and Abdul Rahim, 2012). The compaction pattern was done 5 times in each direction alternately to attain the desired density. Compaction should be completed within 15 min. of spreading and 45 min. from the initial mixing. After the 1st layer was compacted, the remaining half of the slab was filled with RCC mix and internal tamping was done to the uncompacted layer.

Curing and Protection

Immediately after final rolling and compaction, the surface of the RCC slab was kept continuously moist for 28 days. The water cure was applied by spreading water over the top and side surface areas once in the morning and in the afternoon. Application of this moisture must be done in a manner that will not wash out or damage the surface of the finished RCC. After spraying, it was then covered by sheet materials canvass.

Obtaining and Testing for Compressive Strength of the cored samples

The cored samples were obtained in accordance with ASTM C42/C 42M Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete. Six (6) cored samples were taken from each RCC slab representing 3-day, 14-day, and 28-day curing time. Personnel from DPWH- Lanao Del Norte, 2nd Engineering District conducted the coring test. After the cores have been drilled, surface drill water was wipe off and allowed the remaining surface moisture to evaporate. In determining the density of each sample, the cored samples were weighed, and the resulted mass was divided by the volume of the core calculated from the average diameter and length. Testing the compressive strength of the core samples was done in the Material Testing Laboratory of MSU-IIT using the Universal Testing Machine (UTM). The test followed the ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

RESULTS AND DISCUSSION

Physical and Chemical Properties of Materials

Shown in Tables 1 and 2 are the results of tests conducted by the researcher to evaluate the physical properties of the fine and coarse aggregates used in the experiment, respectively.

Table 1

Properties of Fine Sand

Fine Sand		
Unit weight (kg/cu.m)	loose	1605
	rodded	1706
Specific Gravity (SSD)		2.645
Absorption, %		2.31

Table 2

Properties of Coarse Aggregates

	3/4 " Coarse Aggregates	
Unit weight (kg/cu.m)	loose	1447
	rodded	1612
Specific Gravity (SSD)		2.6495
Absorption, %		1.98

XRF Fused Bead test was conducted to test the physical and chemical properties of a 5-kg sample submitted fly ash and the results are shown below in Table 3.

Table 3

Properties of Fly Ash (Lafarge, Philippines)

SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	K2O	Na2O	TiO2	P2O5	LOI	IR	Moisture	PAI
39.04	16.29	22.49	9.42	1.66	1.2	0.92	0.12	1.15	0.08	6.65	65.24	1.95	92

Table 4

Properties of Portland Cement Type 1 (Holcim, Philippines)

Chemical Contents													
LOI	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	K2O	Na2O	TiO2	Mn2O3	P2O5	Total	FCaO
4.49	22.19	5.81	2.96	59.09	2.09	2.38	0.64	0.25	0.29	0.08	0.06	100.30	1.10

Fineness		Other Properties			Vicat Setting Time		Compressive Strength			
Blaine	R45(325M)	WR (NC)	Flow (Work)	Expansion	Initial	Final	3D	7D	28D	Density
376.67	3765.56	13.36	26.17	107.67	0.06	128.22	259.67	18.98	25.53	33.73	3.00

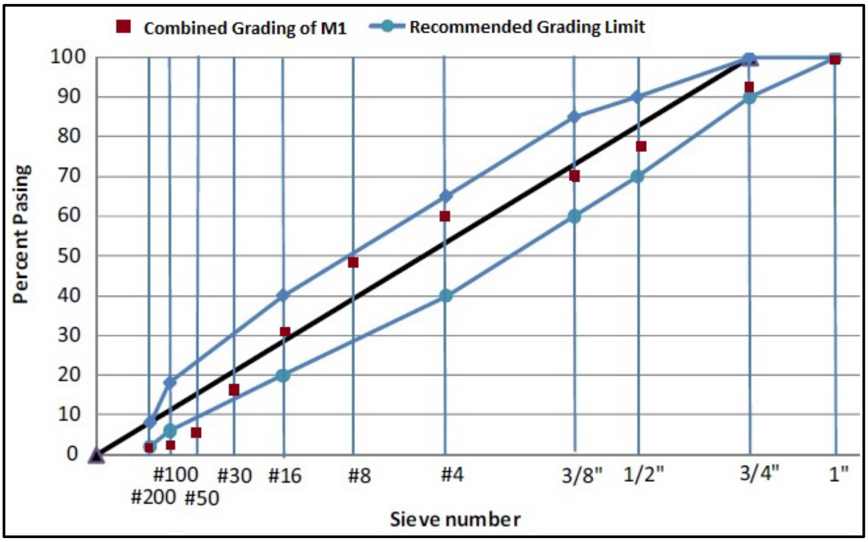
Above are the results chemical and physical analyses of Type 1 Portland cement conducted by the laboratory personnel of Holcim Cement in Holcim Plant, Iligan City.

Combined Aggregate Grading Limit

Shown in Figures 6 and 7 are the graphs of combined grading of aggregates for M1 and M2 respectively. In the 1st graph shown in Figure 6, aggregates finer than No. 50 sieve mesh are beyond the recommended grading limit. This is because the researcher utilized the commercially available aggregates of crushed ¾" and natural sand in the local market.

Figure 6

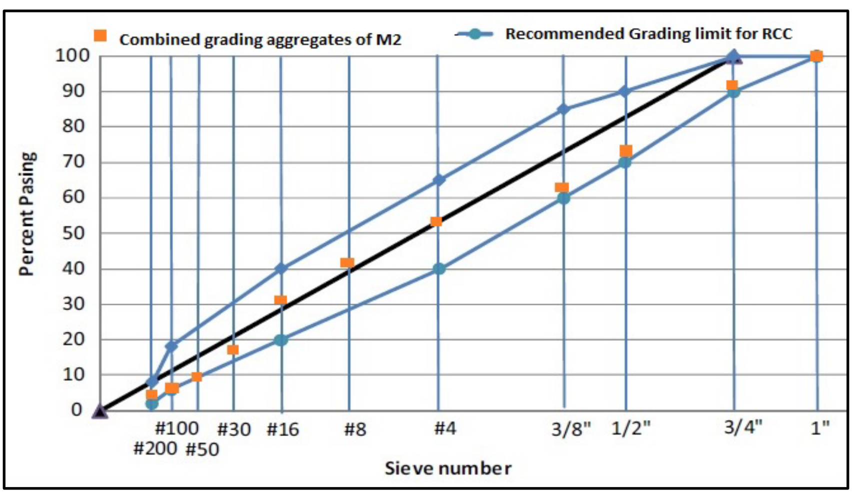
Combined Grading of Aggregates in M1



While in the 2nd graph in Figure 7, almost all the aggregates are within the suggested limit. In this mixture, the researcher added pulverized sand and ½" rounded aggregate to have a denser aggregates combination. A larger percentage of fines is used to fill voids and contribute to compactibility of the RCC mix (Adaska, 2006).

Figure 7

Combined Grading of Aggregates in M2



Maximum Moisture Density Curve

After performing modified proctor test as stipulated in ASTM D-1557, the maximum dry density (MDD) and the optimum moisture content (OMC) were obtained from the plotted graphs in Figure 8 for the M1 and Figure 9 for the M2. The MDD is the peak value of the curve, and the vertical component of that value is the OMC.

Figure 8

Moisture Density Curve for M1

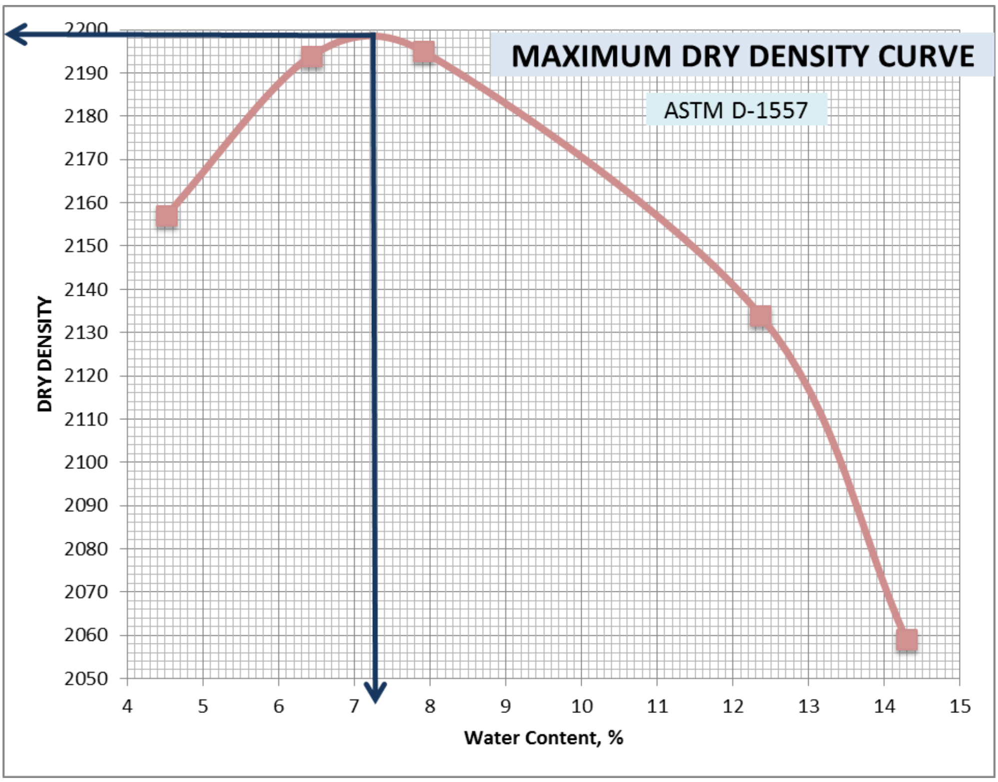
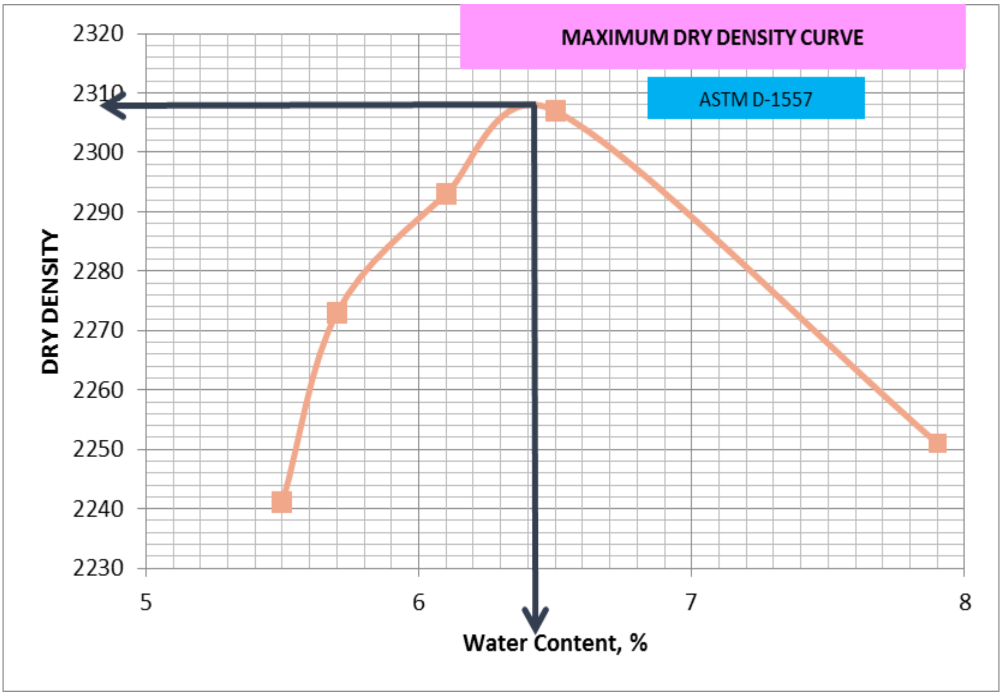


Figure 9

Moisture Density Curve for M2



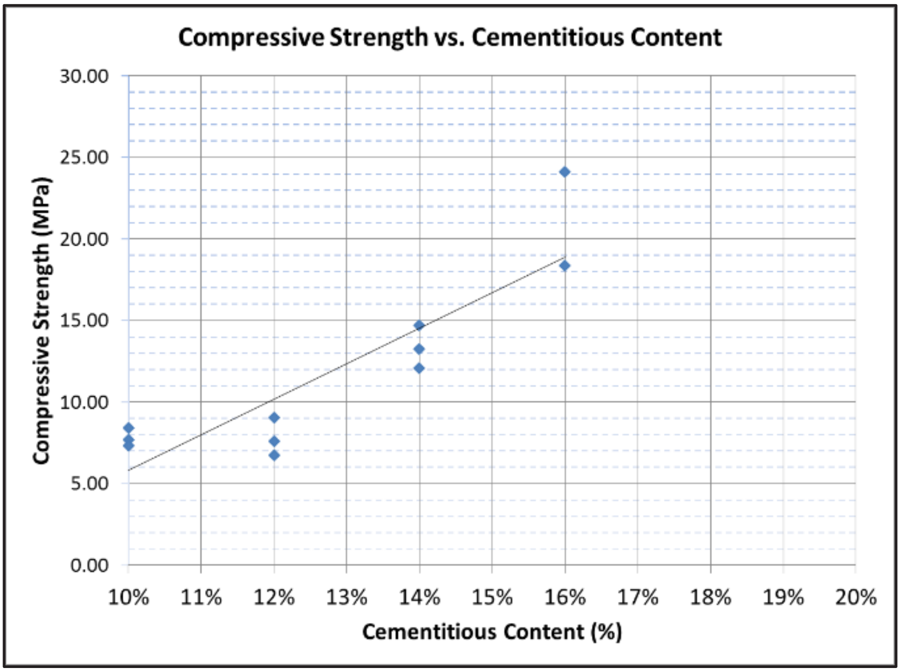
In Figure 8, MDD is equal to 2,198 kg/m^3 with an OMC of 7.3%. While in Figure 9, maximum dry density (MDD) is 2,309kg/m^3 and optimum moisture content (OMC) is equal to 6.4%. The MDD of M2 is greater than the MDD of M1 due to the fact that M2 has more dense aggregates than M1. It is the discretion of the researcher to choose and use M2 for the construction of RCC slab.

Compressive Strength of Roller Compacted Concrete

Shown in Figure 10 is the compressive strength of RCC cylinders casted in the laboratory using a vibrating hammer (ASTM C1435). Based on the graph, only 16% cementitious content passed the design strength which is 21 MPa. The researcher then used 16% cementitious content in constructing the RCC slab. From the same graph, compressive strength of RCC is directly proportional to the percentage of cementitious content used in the mix. As the % of cementitious material content increases, the breaking compressive strength also increases while maintaining the amount of the other materials used.

Figure 10

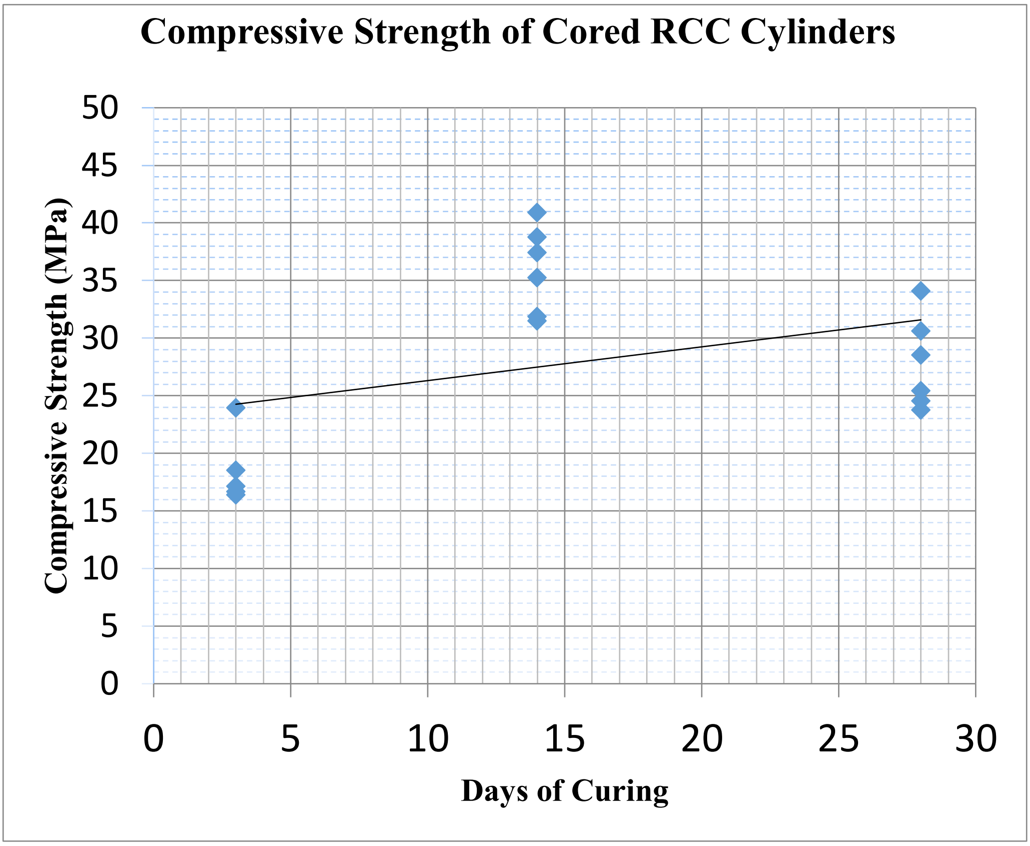
Compressive Strength of RCC cylinders



Compressive force (KN) applied on the cored RCC cylinders are shown in Figure 10 with the corresponding number of days it was cured. It was observed that the 3-day curing duration reached 130.67 KN, 14days was 254.97 KN, and 28days was 197.42 KN.

Figure 11

Compressive Force (KN) applied on RCC cored samples



In Figure 11, are the compressive strengths of cored RCC samples. From the graph, the average compressive strength attained of each core samples in Megapascal (MPa) and pounds per inch squared (psi) is shown. There are six (6) core samples drilled from each slab representing the three (3) duration of curing: 3 days, 14 days, and 28 days. The area for all of the cores is 7,088.24mm^2.

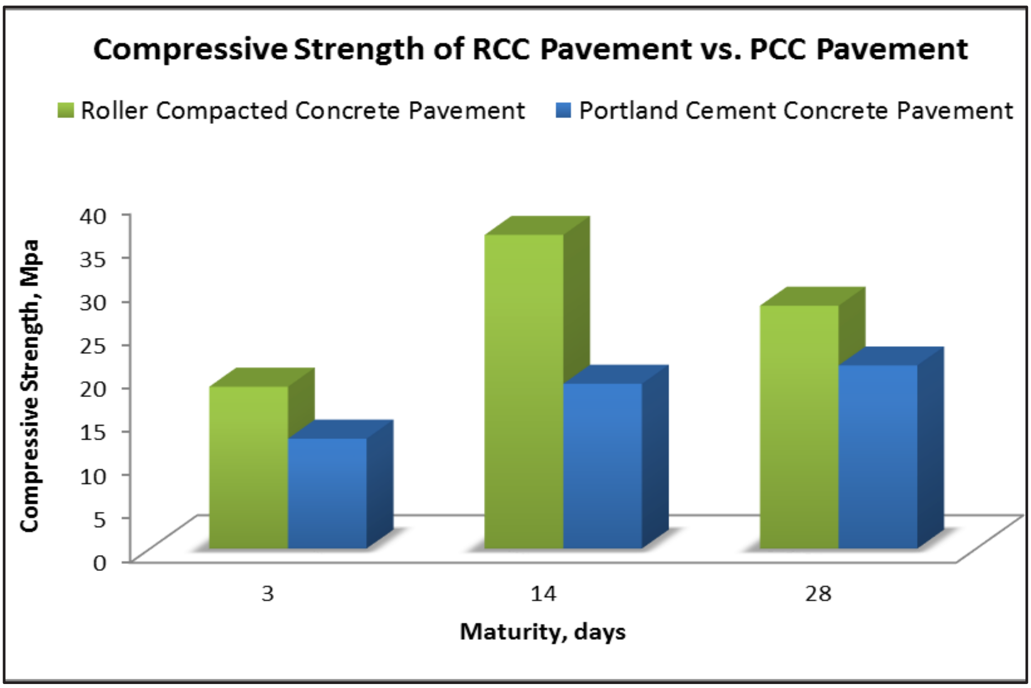
For 3 days curing, the average compressive strength was 18.44 MPa, for 14 days the strength achieved was 35.97 MPa, and for 28 days, it was 27.85 MPa. It is noticeable that the compressive strength for 3 days curing duration was already high.

According to Atis (2005), the strength of concrete with fly ash attained satisfactory or higher compressive and flexural strength than the normal concrete without fly ash because it increases workability and density of the RCC. From the graph above, compressive strength of RCC at any duration of curing is high and from 3-day strength, it increases to 40.65% on the 28th day of curing, attaining a compressive strength of 27.85 MPa.

The Department of Public Works and Highways has published Quality Control Manual on Concrete and Steel Bridge Structures (2014) and developed a graph depicting the compressive breaking strength of concrete at various ages. Figure 12, shows the comparison between the attained strength of RCC with the strength of an ordinary portland cement concrete.

Figure 12

Compressive Strength of Cored RCC vs. Design Strength from DPWH



In 3 days of maturity, the strength of RCC is 32% higher than the predicted strength of ordinary concrete. While in 14 days of maturity, RCC is 47% higher than the designed compressive strength of ordinary concrete.

Figure 12 shows the comparison between the attained strength of RCC with the strength of an ordinary portland cement concrete based on the graph presented by the DPWH. In 3-day curing duration, the 3 days maturity strength of RCC is 38.2% higher than the predicted strength of ordinary Portland Cement concrete. While in 14 days maturity, RCC is 62.2% higher. In 28 days curing time, Roller Compacted Concrete is 28.05% higher than the designed compressive strength.

It is noticeable that in all days of maturity or curing, RCC is higher than PCC in terms of compressive strength. This result supported the conclusion of Atis (2004) that concrete with fly ash attained satisfactory or higher compressive and tensile strengths when compared with normal portland cement (NPC) concrete. and Though 28-day strength being lesser than the 14-day strength, it is still higher than the designed strength of 21 MPa.

CONCLUSION AND RECOMMENDATION

After conducting the experiment and interpreting the obtained results, the following conclusions and recommendations can be drawn.

A combination of aggregates following the recommended grading limit results to a well-dense Roller Compacted Concrete mix. When using the 2nd mix (M2), maximum dry density of RCC mix is 2,309kg/m^3 and an optimum moisture content of 6.4%. While for the 1st mix MDD is 2,198 kg/m^3 with an OMC of 7.3%. The pulverized sand and the fly ash contributed in the differences of the attained MDD and OMC of M1 and M2. The compressive strength of RCC cylinders cast in the laboratory is the basis for selecting the percentage of cementitious content used in constructing the RCC slab. The designed compressive strength has a cementitious content of 16%. The compressive strength of cored RCC at 3 days curing duration is 18.45 MPa, for 14-day curing is 35.97 MPa, while for 28-day curing is 27.85 MPa. The compressive strengths of the RCC cored samples exceed the designed strength of Class “A” concrete which is 21 MPa at 28-day curing. Using the correction factor formulated by ACI (2003), the breaking strength of RCC cored samples are converted to in-place compressive strength. Thus, the in-place compressive strength of RCC at 28 days is 29.43 MPa.

Based on the 3-day compressive strength of RCC cored samples, RCC obtained 88.4% of the designed strength, while at 14-day curing of PCC, the strength is at least 90% of the design strength. Therefore, RCC pavement can be opened to light traffic 3 days after construction.

The researcher recommends for a longer period of observation and extensive days of curing so that the behavior of the formulated RCC mix can be observed and determined. It is also recommended to use other design mixes, and incorporate more types of admixtures and other industrial by-products, and compare the results with the existing design mix. Furthermore, it is suggested to explore other mix proportions in utilizing fly ash to maximize its potential in improving the strength concrete and investigate further the compaction of roller compacted concrete, and formulate a guideline that will utilize the advantages of RCC to be used in the Philippines.

REFERENCES

ACI Committee 214, (2003). “Guide for Obtaining Cores and Interpreting Compressive Strength Results”, ACI 214.4R-03, American Concrete Institute, Farmington Hills, MI, USA, 16 pp.

Adaska, W. (2006). Roller-compacted concrete (RCC). Portland Cement Association Research $Development Information, 2975 (51), 595-604.

American Concrete Institute. (2002). Guide for selecting proportions for no-slump concete (ACI 211.3R-02). Michigan, USA. Retrieved from http://www.icie.ir/files/filebox/211.3r_02.pdf

ASTM C-127-01, (2001). Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate. ASTM International. West Conshohocken, PA, DOI: 10.1520/C0127-01.Retrieved from www.astm.org.

ASTM C-128-01, (2001). Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate. ASTM International. West Conshohocken, PA, DOI: 10.1520/C0128-01.Retrieved from www.astm.org.

ASTM C-136-01, (2001). Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International. West Conshohocken, PA, DOI: 10.1520/C0136-01.Retrieved from www.astm.org.

ASTM C39/C39M-03. (2003). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International. West Conshohocken, PA, DOI: 10.1520/ C0039_C0039M-03.Retrieved from www.astm.org.

ASTM C42/C 42M Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete. ASTM International. West Conshohocken, PA, DOI: 10.1520/ C0039_C0039M-03.Retrieved from www.astm.org

ASTM D-1557 – 12. (2012*). Standard test methods for laboratory compaction characteristics of soil using modified effort.* ASTM International. West Conshohocken, PA, DOI: 10.1520/D1557-12.Retrieved from www.astm.org.

Atis, Cengiz Duran, *Strength properties of high-volume fly ash roller compacted and workable concrete, and influence of curing condition.* Cement and Concrete Research .35 (2005) 1112– 1121

Dam, T.V., Taylor, P., Fick, G., Gress, D., VanGeem, M., Lorenz, E. (2012), *Sustainable concrete pavements: A manual of practice.* Final Report/ Manual. National Concrete Pavement Technology Center, Iowa State University, Retrieved Jan. 2, 2013, from http://www.nrmca.org/sustainability/Sustainable%20Concrete% 20Pavement .pdf

Harrington, D., Abdo, F., Adaska, W., & Hazaree, C. (2010). *Guide for roller-compacted concrete pavements.* Institute for Transportation, Iowa State University Portland Cement Association, Retrieved Jan. 3, 2013, from http://members.cement.org/EBiz55/ProductCatalog/Product.aspx?ID=1626

Philippines Department of Public Works and Highways. (2014). *Quality control manual on concrete and steel bridge structures 2nd edition*. Retrieved from http://www.dpwh.gov.ph/jica/pdf/Quality%20Control%20Manual%20on%20Concrete%20and%20Steel%20Bridge%20Structuers_2nd%20Edition.pdfhttp://www.dpwh.gov.ph/jica/pdf/Quality%20Control%20Manual%20on%20Concrete%20and%20Steel%20Bridge%20Structuers_2nd%20Edition.pdf

Sarsam, S., Al-Rawi, A., Abdul Rahim, A. (2012). Laboratory investigation on roller compaction technique in concrete construction. *Journal of Engineering v18 (4).* Retrived September 16, 2013 from http://www.coeng.uobaghdad.edu.iq/uploads/Juornal/2012/April/Laboratory%20Investigation%20on%20Roller%20Compaction%20Technique%20in.pdf