Determining the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of Roller-Compacted Concrete: A Basis of Its Optimum Design Mix

Carmel S. Burlat
Department of Civil Engineering, Caraga State University

Marc Lin F. Abonales
Department of Civil Engineering, Caraga State University

Shelah Grace C. Hebra
Department of Civil Engineering, Caraga State University

Mark Crysler F. Valeros
Department of Civil Engineering, Caraga State University

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Determining the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of Roller-Compacted Concrete: A Basis of its Optimum Design Mix

Carmel S. Burlat[1,2], Marc Lin F. Abonales[1,2], Shelah Grace C. Hebra[1,2], Mark Crysler F. Valeros[1]
[1]Department of Civil Engineering, Caraga State University
[2]Center for Resource Assessment, Analytics and Emerging Technologies (CREATE), Caraga State University
Corresponding author email: csburlat@carsu.edu.ph; mlfabonales@carsu.edu.ph

Abstract:
Roller-Compacted Concrete (RCC) emerges as a viable solution, offering durability and cost-efficiency while minimizing environmental impact. This study evaluates RCC's performance in the Philippines, focusing on two mixes—M1 and M2—designed with different aggregate compositions and cementitious materials. The study also examines the physical and chemical properties of materials like Class F fly ash (for M2) and Type I Portland cement (for both M1 and M2), essential components enhancing RCC's sustainability and performance. M2, characterized by a higher Maximum Dry Density (MDD) of 2,309 kg/m³ and lower Optimum Moisture Content (OMC) of 6.4%, demonstrates superior compactibility and potential strength compared to M1. Findings highlight M2 as the optimal mix for RCC slabs, emphasizing its potential for reducing construction time and costs while meeting long-term durability requirements. Recommendations include promoting RCC adoption, optimizing material selection, and investing in research to further enhance sustainability and performance in the pavement industry.

Keywords: Roller-Compacted Concrete, Cementitious Materials, Fly Ash, Maximum Dry Density, Optimum Moisture Content

1. INTRODUCTION

Societies nowadays are making ways to meet the challenge of adopting sustainable practices in everyday living. Sustainability is now considered as a factor in almost every decision making concerning the use of energy, natural resources and even man-made capitals. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1][24]. Pavement industry is one of the areas where sustainability must be practiced, to maintain a balance in the economic viability and the environmental and social obligations of a particular pavement project [2]. The builders and engineers responsible for the management, design, construction, maintenance, and rehabilitation of the deteriorating network of pavements are overwhelmed, recognizing that the current approach to solving problems inherent in the nation's pavement infrastructure is not sustainable [16][17]. The application of truly sustainable pavement solutions that result in minimized economic cost over the life cycle, decreased environmental impact, and improved societal benefit, while maintaining a high serviceability over a long period of time is needed in the industry [18][19]. 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 emitted to the environment. 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 and of lesser water-cement ratio compared to conventional concrete [3][8]. 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. Due to its lower water-cement ratio, the carbon footprint is reduced [2][20]. The need for addressing environmental issues has become critical as cities struggle with issues like carbon emissions. Fly ash possesses several characteristics that render it an environmentally viable alternative. Firstly, its use decreases the demand for conventional cement, which is a significant source of carbon dioxide emissions. By partially substituting cement with fly ash, the production of concrete can substantially lower its carbon footprint. Moreover, fly ash enhances the workability, durability, and chemical resistance of construction materials [14][22][23]. With these advantages in sustainability, economics, and construction, determining its optimum moisture content and maximum dry density as a basis on its optimum design mix, construction time and production unit cost is a massive significance in choosing a better pavement in meeting and providing the needs of the society [21].

2. METHODOLOGY

The general methodology of this study includes the following procedure such as determination of the physical properties of materials to be used, choosing well-graded aggregates for combined grading, selection of cementitious materials content, development a moisture-density curve, determination of the Optimum Moisture Content. In determining the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of RCC, two (2) types of mixes was used. Mix 1 (M1) was composed of natural sand, and ¾" crushed gravel, Type 1 Portland cement and water. Mix 2 (M2) was composed of pulverized sand, natural sand, 1/2" rounded gravel, ¾" crushed gravel, and the cementitious material for M2 was made of fly ash, Type I Portland Cement and water.

2.1 Materials used in the Experiment

The aggregates used in this study was taken from the quarries near Mandulog River, Brgy. Hinaplanon, Iligan City. The coarse aggregates used in this study were both angular and rounded, while fine aggregates were natural and rounded in shape. Natural sand, composed mainly of uncrushed rounded particles, is commonly chosen for concrete mixes due to its affordability, widespread availability, and ease of blending with other materials [25]. This makes it a practical choice for various construction applications. The cementitious material used was Type I Portland cement manufactured by Holcim Philippines, Lugait Plant, while the Fly Ash used was taken from STEAG Power Plant, Villanueva, Misamis Oriental. Pulverized sand was used in this research to cater the aggregate requirements passing No. 50 which is finer in the sieve mesh. Pulverizing the sand was done in the Holcim Cement, Lugait Plant. The water used was from the Iligan City Waterworks System (ICWS).

2.2 Determination of the Physical Properties of Materials Used

2.2.1 Tests for Sieve Analysis and Unit Weight of Fine and Coarse Aggregates

To produce high quality RCC, both the coarse and fine aggregate fractions shall be composed of hard and durable particles. Sieve analysis was evaluated using American Society for Testing and Materials (ASTM) Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (C 136) [12]. The testing was conducted in the MSU-IIT Civil Engineering Laboratory using the Mechanical shaker from Metallurgical Engineering Department.

2.2.2 Determination of Specific Gravity and Absorption of Fine and Coarse Aggregates

To determine the specific gravity and absorption of fine and coarse aggregates, ASTM C 128-01 Test Method for Density [11], Relative Density (Specific Gravity), and Absorption of Fine Aggregates and ASTM C127-01 Test Method for Density [10], Relative Density (Specific Gravity), and Absorption of Coarse Aggregates were followed. It was performed in the MSU-IIT Civil Engineering Laboratory.

2.2.3 Determination of Physical and Chemical Properties of Fly Ash

A 5-kg fly ash was submitted to Lafarge Iligan Inc. located at Barangay Kiwalan, Iligan City. XRF Fused Bead test was conducted to tests its physical and chemical analysis. Lafarge Iligan Inc. is using the same fly ash from STEAG Power Plant as an additive to its cementitious content in cement production. Max moisture [%], Max LOI [%], Max SO3 [%], Max MgO [%], Max Alkali [%], Min SAF [%], Pozzolanic activity index (PAI) were all determined to classify the type of fly ash according to ASTM C 618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete [13].

2.2.4 Determination of Physical and Chemical Properties of Cement

Type I Portland cement manufactured by Holcim Cement was used in the experiment. The physical and chemical testing of Portland cement was done in the laboratory of the Holcim Cement. ASTM C114 - Standard Test Methods for Chemical Analysis of Hydraulic Cement [9] and ASTM C109 - Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) were all conducted to determine the physical and chemical characteristics of cement.

2.3 Selection of Well-Graded Aggregates for Combined Grading

To have a quality RCC pavement mixture, dry coarse and fine aggregates were combined to yield a grading limit following the American Concrete Institute (ACI) recommended aggregate gradation shown in Table 1. It is important that the aggregates gradation is within the specified maximum and minimum cumulative percent passing to yield a well dense mix.

Table 1. Recommended RCC Pavement combined aggregate grading limit

Sieve Size		**Cumulative Percent Passing**	
Inch	Millimeter	Minimum	Maximum
3/4"	19.00	100	100
1/2"	12.50	70	90
3/8"	9.50	60	85
#4	4.75	40	60
#8	2.36	35	55
#16	1.18	20	40
#30	0.60	15	35
#50	0.30	8	20
#100	0.150	6	18
#200	0.075	2	8

2.4 Selection of Cementitious Materials Content

The choice of cementitious materials is based on the compressive or flexural strength specifications of the project, economic considerations, availability of the materials, and production consideration [3]. For secondary roads, a compressive strength of 3000 psi and a flexural strength ranging from 600 to 700 psi are already acceptable. This pre-determined strength corresponds to 10 to 17% by mass of dry aggregates [4]. 3000 psi was used as a design compressive strength for this study [5]. The cementitious materials are expressed as a percent of total dry materials as follows:

$$Cementitious\ materials\ (\%) = \frac{a}{(a+b)} x\ 100 \quad (1)$$

Where: a = weight of cementitious content
b = weight of oven-dried aggregates

2.5 Development of Moisture-Density Curve

Using the combined aggregate grading and the cementitious material content, the ASTM D-1557 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort was performed. For almost all the aggregates, the optimum moisture content ranges from 5 to 8% and it is computed as follows:

$$Moisture\ Content\ (\%) = \frac{c}{(a+b)} x\ 100 \qquad (2)$$

Where: a = weight of cementitious content
b = weight of oven-dried aggregates
c = weight of water

The dry unit weight of each sample was plotted obtained from ASTM D-1557 and its respective moisture content. A smooth curve was drawn through the plotted points.

2.6 Determination of the Optimum Moisture Content

Optimum moisture content was determined from the plotted compaction curve. The peak value of the generated curve along the y-axis is the Maximum Dry Density (MDD), and the corresponding x-axis value is the Optimum Moisture Content (OMC) of the mix.

3. RESULTS AND DISCUSSION

3.1 Physical and Chemical Properties of Materials used

Shown in Table 2 are the results of the tests to evaluate the physical properties of the aggregates used in the experiment. In the 2nd and 3rd columns are the loose and rodded unit weight. The natural sand has the highest % of absorption followed by the ¾" coarse aggregates.

Table 2. Properties of Fine Sand, ½" Coarse Aggregates, and ¾" Coarse Aggregates

	Unit Weight, kg/ m^3		Specific Gravity	Absorption, %
	Loose	Rodded		
3/4" coarse aggregates	1446.74	1612.06	2.6495	1.98
1/2" coarse aggregates	1281	1385	2.695	1.275
Sand aggregates	1604.33	1705.22	2.645	2.31

Table 3. Limits of Standards for the Chemical Composition and Physical Properties of Fly Ash

	Fly Ash	Specification ASTM C 618
Max moisture	1.95	3.00
Max LOI (%)	6.65	6.0A
Max SO_3 (%)	1.2	5.00
Max MgO (%)	1.66	5.00
Max Alkali (%)	1.04	1.50
Min SAF (%)	77.82	70, minimum
Pozzolanic activity index (PAI) min (%)	92	75, minimum

It can be observed from Table 3 that the fly ash from STEAG State Power Inc. is classified as a Class F fly ash since it passed all the maximum or minimum values specified under Class F. Pozzolanic activity index (PAI) measures the strength of the fly ash and indicates specification compliance. The PAI of fly ash is 92% at 28 day-strength which is greater than the minimum required strength index at 75% for 28 days. The Alkali content is composed of potassium oxides (K_2O) and Sodium oxides (Na_2O) with value of 1.04%.

The results of physical and chemical tests conducted on the Class F fly ash are shown below in Table 4.

Table 4. Properties of Fly Ash (Lafarge, Philippines)

SiO_2	39.04
Al_2O_3	16.29
Fe_2O_3	22.49
CaO	9.42
MgO	1.66
SO_3	1.2
K_2O	0.92
LOI	6.65
IR	65.24
Moisture	1.95
PAI	92
Na_2O	0.12
TiO_2	1.15
P_2O_5	0.08

Tables 5 and 6 shows the results of chemical and physical analyses of Type I Portland cement conducted by the laboratory personnel of Holcim Cement. The mechanical strength of the cement mortar at 3 days is 18.98 MPa while for 28 days is 33.73 MPa, with a loss on ignition (LOI) of 4.49% and a density of 3.00 kg/cu.m.

Table 5. Physical Properties of Portland Cement Type 1 (Holcim, Philippines)

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

Table 6. Chemical Properties of Portland Cement Type 1 (Holcim, Philippines)

Chemical Contents						
LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
4.49	22.19	5.81	2.96	59.09	2.09	2.38
K_2O	Na_2O	TiO_2	Mn_2O_3	P_2O_5	Total	FCaO
0.64	0.25	0.29	0.08	0.06	100.30	1.10

3.2 Combined Aggregate Grading Limit

Shown in Figures 1 and 2 are the graphs of combined grading of aggregates for M1 and M2 respectively. In the 1st graph, aggregates finer than No. 50 sieve mesh is beyond the recommended grading limit [3]. This is because the researcher utilized the only commercially available aggregates of crushed ¾" and natural sand in the vicinity. However, in the 2nd graph 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. The larger percentage of fines were used to fill voids and contributed to the compactibility or the ability of the RCC mix to be compacted [6].

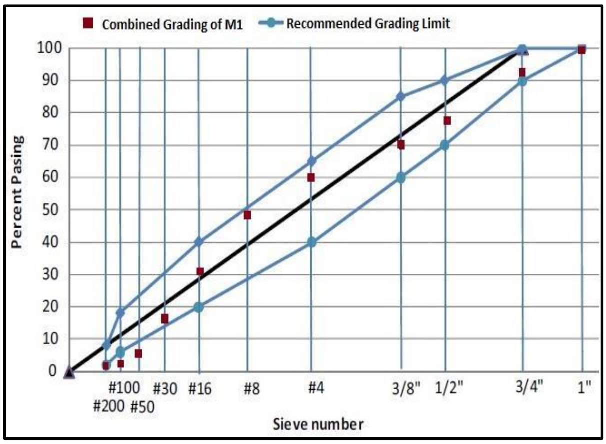

Fig. 1. Combined Grading of Aggregates in M1

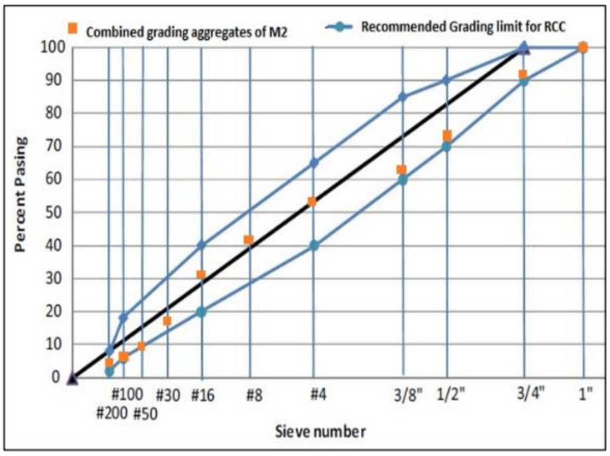

Fig. 2. Combined Grading of Aggregates in M2

Table 7. % Passing of Aggregate Gradation

Sieve	M1, % Passing	M2, % Passing	Standard Grading
1"	99.6	99.54	100-100
3/4	91.6	91.4	82-100
1/2	77.0	72.8	72-93
3/8	70.5	64.7	66-85
#4	59.4	53.4	51-69
#8	47.0	41.8	38-56
#16	31.5	31.5	28-46
#30	18.3	19.8	18-36
#50	5.4	8.7	11-27
#100	1.5	6.9	6-18
#200	0.7	2.5	2-8
Pan	0.0	0.0	0.0

In Table 7 is the combined grading of aggregates for M1 and M2. In the 2nd column, aggregates finer than No.50 sieve mesh is beyond the recommended grading limit. While in the 3rd column, almost all the aggregates are within the suggested limit. A larger percentage of fines is used to fill voids and contribute to compactibility of the RCC mix [4].

3.3 Maximum Moisture Density Curve

After performing modified proctor test (ASTM D 1557), maximum dry density (MDD) and the optimum moisture content (OMC) of the mix were obtained from the plotted graphs in Figure 3 for the M1 and Figure 4 for the M2. The MDD is the peak value of the curve along the y-axis, and the corresponding value along the x-axis is the OMC. In Figure 3, MDD of M1 is equal to 2,198 kg/m^3 with an OMC of 7.3%. However, in Figure 4, MDD of M2 is 2,309 kg/m^3 and OMC is equal to 6.4%. The MDD of M2 is greater than the MDD of M1 due to the addition of pulverized sand in M2. Thus, making M2 denser than M1. With this, fly ash enhances both the mechanical and physical properties of concrete. It suggests that an optimal substitution dosage of 10% of ordinary Portland cement with fly ash can effectively improve these characteristics in basic concrete applications [15].

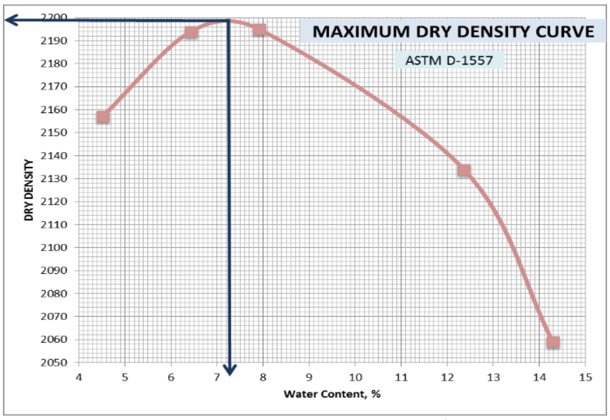

Fig. 3. Moisture Density Curve for M1

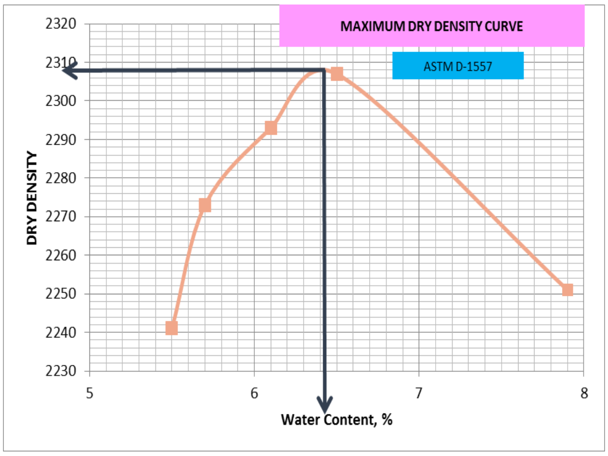

Fig. 4. Moisture Density Curve for M2

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

The pavement industry plays a critical role in infrastructure development, requiring sustainable practices to meet environmental and economic challenges. In this context, Roller-Compacted Concrete (RCC) has emerged as a promising solution. Unlike traditional concrete, RCC is characterized by its zero-slump nature and unique mix proportions, making it well-suited for various construction applications, including pavements, dams, and industrial flooring. In the Philippines, RCC represents a novel approach to infrastructure development, offering durability and cost-efficiency without the need for forms or reinforcement. By achieving a Maximum Dry Density (MDD) of 2,309 kg/m^3 and an Optimum Moisture Content (OMC) of 6.4%, M2 exhibits superior density and potential strength compared to its counterpart, M1. These characteristics are crucial for ensuring the longevity and performance of RCC structures under varying environmental conditions. According to Shafigh, P. et.al, the roller-compacted concrete pavement (RCCP) achieved its highest dry density at 5.7% moisture content, whereas the optimal mechanical performance, lowest porosity, and minimal water absorption occurred at 5% moisture content [7]. This observation suggests that while maximum dry density is typically desirable for compacted materials like RCCP, other important performance characteristics such as mechanical strength and durability are better optimized at slightly lower moisture levels. Therefore, the study concludes that RCCP can be effectively designed and constructed with a moisture content below the level required for achieving maximum dry density, ensuring both workability during construction and superior long-term performance in service. The physical and chemical properties of the materials used in the study further underscore their suitability for RCC applications. Fly ash, a key supplementary cementitious material, was analyzed for its composition and pozzolanic activity index (PAI). The results confirm that the fly ash utilized meets ASTM standards for Class F classification, indicating high reactivity and contributing significantly to concrete strength and durability. Similarly, Type I Portland cement, characterized by its specified chemical composition and compressive strength parameters, complements the aggregate components to form a robust RCC matrix.

In conclusion, the comprehensive evaluation of these materials reveals their alignment with the stringent requirements of sustainable infrastructure development in the Philippines. M2 emerges as the preferred RCC mix for slab production due to its superior aggregate grading and densification characteristics. This selection not only enhances construction efficiency but also ensures long-term performance and resilience against environmental stresses. By embracing RCC and similar innovative materials, the pavement industry in the Philippines can advance towards greener and more resilient infrastructure solutions. These advancements not only reduce carbon footprint but also promote economic efficiency and longevity in construction practices.

4.2 Recommendations

Based on the findings and conclusions, several recommendations can be made to further enhance sustainability and optimize performance in the pavement industry:

1. Promote the Use of RCC:

Advocate for the wider adoption of Roller Compacted Concrete (RCC) in infrastructure projects across the Philippines. Highlight its benefits such as reduced construction time, lower costs, and minimal environmental impact due to its zero-slump nature and simplified construction process.

2. Optimize Material Selection:

Continue to prioritize the use of sustainable materials like Class F fly ash and Type I Portland cement in RCC mixes. These materials have demonstrated suitable physical and chemical properties, contributing to the strength, durability, and environmental performance of RCC structures.

3. Enhance Aggregate Grading:

Emphasize the importance of adhering to recommended aggregate gradation limits, as demonstrated by M2 in the study. Proper aggregate grading enhances the compactibility and workability of RCC mixes, leading to improved structural integrity and performance.

4. Invest in Research and Development:

Allocate resources towards further research and development of RCC technologies and materials tailored to local conditions and infrastructure needs. Explore advancements in mix designs, additives, and construction techniques to continually improve RCC's performance and sustainability.

5. Educate Stakeholders:

Provide training and educational programs for engineers, contractors, and policymakers on the benefits and proper implementation of RCC. Foster a deeper understanding of its applications, design considerations, and maintenance requirements to ensure successful adoption in future projects.

6. Monitor Performance and Longevity:

Establish a framework for monitoring the performance and longevity of RCC pavements and structures over time. Conduct regular inspections and evaluations to assess durability, resistance to wear and environmental factors, and overall lifecycle cost-effectiveness compared to conventional concrete solutions.

7. Collaborate with Industry Partners:

Foster partnerships between government agencies, private sector stakeholders, and academic institutions to facilitate knowledge sharing and innovation in RCC technologies. Collaborative efforts can accelerate the adoption of sustainable practices and standards across the pavement industry.

Implementing these recommendations will not only support the sustainable development goals of the pavement industry in the Philippines but also pave the way for resilient, cost-effective, and environmentally friendly infrastructure solutions. By embracing RCC and advancing its use with careful material selection and ongoing research, the industry can contribute significantly to sustainable urban development and infrastructure resilience in the years to come.

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