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EVALUATION OF ROLLER COMPACTED CONCRETE (RCC) MIX DESIGN AND METHODS IN INDONESIA: A COMPARISON OF LABORATORY AND ON-SITE TRIALS

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ABSTRACT: Roller-compacted concrete (RCC) is an alternative method for dam construction that aims to reduce construction time and costs. Despite its advantages, RCC dams have yet to be constructed in Indonesia. While numerous guidebooks provide information on materials and mix designs, a significant challenge remains in utilizing locally accessible materials near dam sites. This research aims to determine the optimal mix design and construction method through laboratory and on-site trials while comparing the results. Laboratory trials used a pan mixer and a vibrating hammer for compaction, whereas the mock-up trial site employed a twin-shaft mixer and a vibratory roller. Samples were prepared using 15 x 30 cm cylindrical specimens and 10 x 20 cm core drills. Various amounts of cementitious material, gravel/sand fractions, and water content were investigated. Both trials revealed that a 50/50 gravel-to-sand ratio and 4% moisture content are optimal. Laboratory trials with Low Cement RCC (LCRCC, 110 kg/m³) achieved a compressive strength of 15 MPa at 150 days, while Medium Cement RCC (MCRCC, 150 and 175 kg/m³) reached 15.41 MPa and 20.86 MPa at 28 days. On-site trials with eight vibratory roller passes achieved 98.3% and 99.2% density and 80.2% and 86.4% compressive strength for MCRCC (150 and 175 kg/m³), respectively. However, large-scale mixing reduced compressive strength by 46.4% and 54.1% for MCRCC (150 and 175 kg/m³). This research highlights RCC's potential for cost and time savings in dam construction but notes unique challenges in Indonesia. Disparities between laboratory and on-site results emphasize the need for safety factors in mix designs and adapting guidebook recommendations to local materials.

Keywords: Roller compacted concrete, Mass concrete, On-site trial, Compressive strength, Density

1. INTRODUCTION

Although RCC has been used in numerous applications of dam construction since the 1970s, it has not yet been used in Indonesia due to the lack of confidence and technical experience in the concrete engineering field. Roller-compacted concrete (RCC) is a unique type of concrete compacted using a roller. For this process to work effectively, the fresh RCC needs to be dry enough to resist sinking under the roller's weight but wet enough to be compacted by its vibration. Moreover, RCC used for the dam is a type of mass concrete, which requires attention to temperature control. A common approach to reduce temperature is the use of pozzolan material to substitute for cement, such as fly ash. Consequently, the hydration process becomes slower, requiring more time to achieve the desired strength.

Adequate compaction is essential to achieve good-quality RCC [1]. However, there are insufficient laboratory compaction methods that can well simulate the actual field conditions. From various literature sources, there are several methods of RCC compaction for laboratory scale such as vibrating hammer, proctor, vibrating table, and pencil vibrator. E. Sengun, B. Alam, R. Shabani, I.O Yaman (2019) suggest that the vibrating hammer method achieves a higher degree of compaction and provides a more accurate representation for low cement dosage mixtures compared to conventional concrete [2]. Laboratory trials were conducted using a vibrating hammer that can produce the ideal density for RCC, while the compaction process using a vibratory roller will certainly result in a different density. U.S. Army Corps of Engineers Roller-Compacted Concrete Manual stated that the distinction in the degree of compaction between laboratory trials and on-site trials may create a gap in the results of RCC properties since strength properties and density of RCC are heavily dependent on the degree of compaction.

LaHucik and Roesler, conducted research demonstrating that there were statistically significant differences in compressive strength between laboratory specimens compacted using a vibrating hammer and field core specimens compacted using vibratory roller, with a confidence level of 95%. They specifically noted that a decrease of 4% in field density, compared to laboratory density, led to a 45% reduction in strength in the field specimens [3]. Based on U.S. Army Engineer Waterways Experiment, core and cylinder testing on several RCC dams provides an overall average of core compressive strength equal to about 75% of the equivalent age cylinder compressive strength.

Laboratory trials are often considered more ideal than on-site trials. This can be attributed to controlled environments in laboratory trials where variables such as temperature, humidity, and equipment precision can be strictly regulated to minimize the risk of accidents or contamination. Whereas high-precision tools and techniques are often not practical or available for on-site trials. Due to the gap between laboratory-scale and on-site-scale, researchers should take a more conservative approach to RCC mix proportions to achieve the required strength of RCC.

Since there is no universal procedure that works best in all cases, the design requirements, availability of materials, and planned placement methods are the key factors that dictate the proportioning of RCC mixes [4]. Mohamed I. Abu-Khashaba, I. Adam, and A. El-Ashaal also investigated the feasibility of constructing RCC dams using locally available materials in Egypt [5]. Their study focused on reducing costs by optimizing material use, which aligns with the objective of this research in Indonesia. However, unlike their study, which primarily explored the possibility of RCC construction, this research highlights the gap between the expected laboratory results and the actual performance of RCC in on-site scale models. By identifying these discrepancies, this study provides a practical safety factor that can be applied to predict the strength of RCC in future dam construction projects in Indonesia. Additionally, unlike their study, this research offers compressive strength data for RCC in scale models, a crucial aspect that was not covered in their paper.

In this study, 110 kg/m^3, 150 kg/m^3, 175 kg/m^3 cementitious content, 40/60, 50/50, 60/40 fractions of gravel/sand, and moisture content of 2.5%, 3.5%, 4%, 5.25%, 6% were investigated. For other comparison, cylindrical test specimens obtained from both a pan mixer (small mixer) and a twin shaft wet mixer (batching plant) are also used for the evaluation. Using RCC with low cementitious material is an effective way to create sustainable, cost-effective, and durable concrete dam structures. By optimizing the mix design and construction techniques, RCC can significantly reduce cement usage, leads to lower CO_2 emissions, as cement production is a significant source of greenhouse gases, thus lowering environmental impact. Additionally, RCC's rapid placement and curing times shorten construction schedules, minimizing environmental disturbances and reducing the overall footprint. This study explored the possibility of constructing Roller Compacted Concrete (RCC) dam in Indonesia using locally available material to reduce cost and found satisfactory and encouraging results by comparing the result of laboratory trials and on-site trials.

This article is organized into four sections. The second section discusses the research significance. The third section presents the methodology of the study. The fourth section provides the results and discussion of the main findings in relation to previous research. The fifth section concludes with a conclusion, and finally, the sixth section shows the acknowledgment of this study.

2. RESEARCH SIGNIFICANCE

Since Roller Compacted Concrete (RCC) has not yet been constructed in Indonesia, this study identifies the feasibility of the mix design using locally available materials. Although numerous studies compare laboratory versus field performance in roller-compacted concrete (RCC), this research focuses on the material limitations in Indonesia, where the nominal maximum size of aggregates (NMSA) is 25 mm, compared to the 75 mm typical or even higher in RCC guidebooks from the US Army and ICOLD. When the correlation between lab and field trials is revealed, future practitioners in Indonesia can predict the strength properties of installed RCC based on laboratory-scale. This investigation is expected to provide a guideline for implementing RCC in dam construction in Indonesia.

3. METHODOLOGY

The flowchart below in Fig.1 details the steps, from material preparation to testing and analysis, for a comprehensive evaluation of RCC performance.

3.1 Materials

The cementitious materials used in this study were Ordinary Portland Cement (OPC) equivalent to ASTM C150 Type I [6] and Fly Ash (FA) obtained from PLTU Suralaya equivalent to ATSM C618 Class F [7]. Initial and final setting times of the cement were 45 and 375 min, respectively. The oxides composition of the PC and FA was determined through X-Ray Fluorescence (XRF) technique. The chemical compositions and physical properties of the cement and FA are listed in Table 1. Natural sand obtained from Ex. Cariu characterized by a nominal size smaller than 4.75 mm, was used as fine aggregate. Crushed stone obtained from Ex. Cariu characterized by a nominal diameter ranging between 4.75 mm and 25 mm, were employed for the coarse fraction. These coarse aggregates were differentiated into two size groups, 4.75 – 10 mm and 10 – 25 mm. To create a well-graded mix of coarse aggregates, 60% of 4.75 – 10 mm size and 40% of 10 – 25 mm size were used. The physical properties of the aggregate are shown in Table 2. Potable water is used in all RCC mixtures.

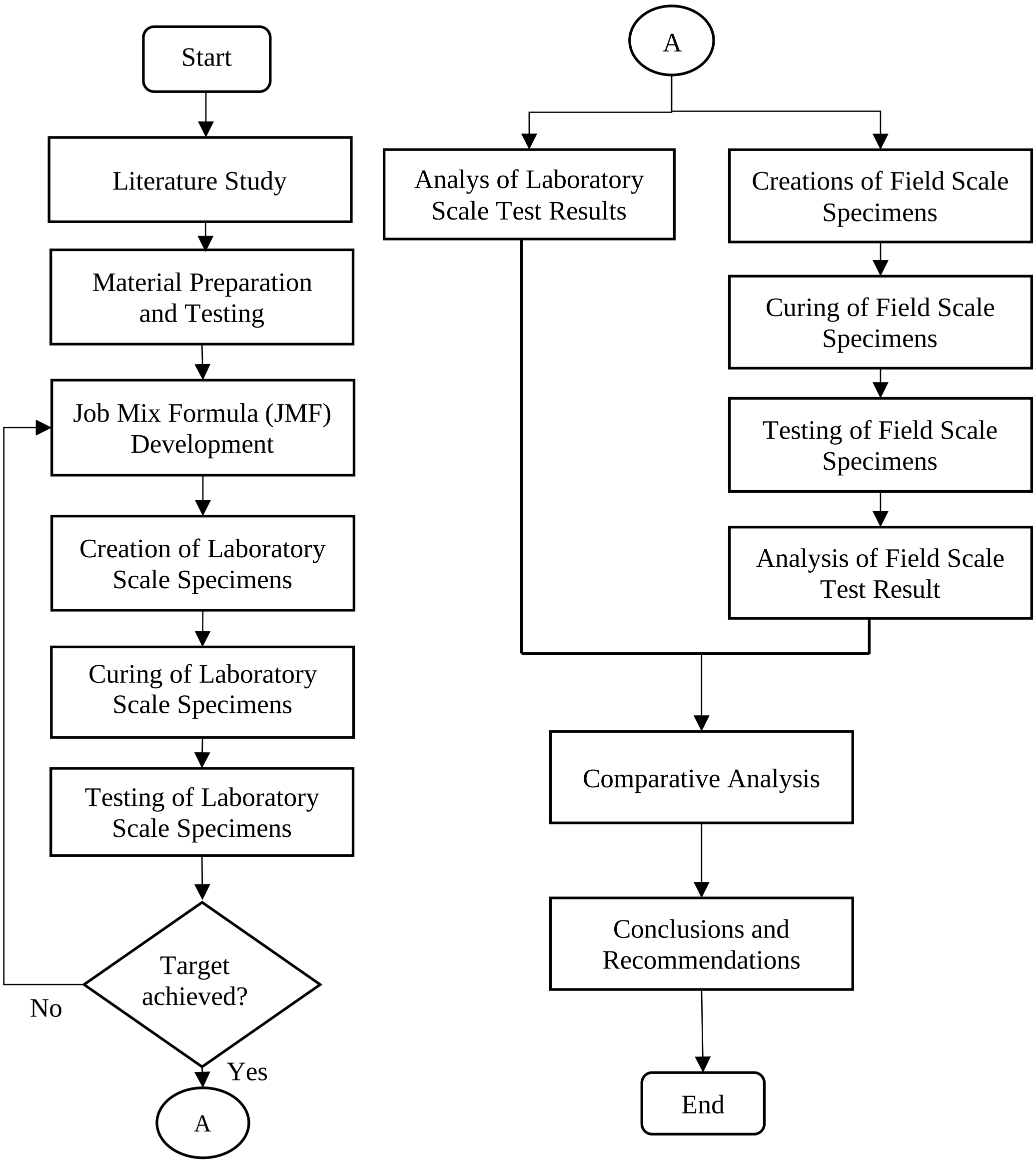

Fig.1 Methodology flowchart

According to ASTM C33, fine aggregate used did not meet the specification for organic impurities in concrete aggregates [8]. Fine aggregate produces a color darker than the standard color, or Organic Plate No. 3 can possibly contain injurious organic impurities [9]. Coarse aggregate also did not satisfy the specific requirements, including water absorption for size 5-10 mm, dry specific gravity and materials finer than 75-µm (No. 200) sieve for both sizes. If the coarse aggregate has a high-water absorption and low dry specific gravity, it indicates that the aggregate is more porous and less dense.

This can lead to a reduction in the overall strength of the RCC [9]. Since these are the materials available in the vicinity of the dam, utilizing these materials is necessary. To address this issue, it is essential to adjust the mix design to compensate for any deviations in aggregate properties to maintain the desired performance characteristics of the RCC.

Table 1 Chemical compositions and physical properties of cement and fly ash

Oxide	Cement (%)	Fly ash (%)
SiO_2	17.70	49.43
Al_2O_3	5.18	27.06
Fe_2O_3	2.66	6.88
CaO	66.6	8.18
MgO	2.78	1.69
Na_2O	0.26	3.12
K_2O	0.80	0.55
TiO_2	0.28	0.85
SO_3	2.77	0.88
Loss on ignition	3.67	0.77
Specific gravity	3.15	2.10

Table 2 Physical properties of aggregates

Properties	Fine aggregates	Coarse aggregates (5-10 mm)	Coarse aggregates (10-25 mm)
Water absorption (%)	0.16	5.06	3.75
Bulk density (kg/m^3)	1591	1395	1437
Specific gravity (SSD)	2.59	2.55	2.57
Specific gravity (dry)	2.58	2.43	2.47
Materials finer than 75-µm (No. 200) sieve (%)	0.85	2.07	1.18
Fineness modulus	2.56	-	-
Organic impurities	No. 4	-	-

Table 3 Mix proportions of RCC

Mix proportions	kg/m^3					
	Cement	Fly ash	Water	Fine aggregate	Coarse aggregate 5-10 mm	Coarse aggregate 10-25 mm
C110 50:50	75	35	150	1211	997	
C150 40:60	100	50	100	1331	533	355
C150 50:50	100	50	100	1110	666	444
C150 60:40	100	50	100	888	799	533
C175 50:50	117	58	117	1089	653	435

3.2 Mix Design

The goal was to achieve a compressive strength of 15 MPa at 150 days, but the project specifications require 7 – 15 MPa in 28 days to ensure that 15 MPa will be reached by 150 days. The target slump of the fresh RCC was 0 mm and the modified Vebe time was 20s. To determine the initial value in proportioning the RCC mixture, the mix design calculation method of the US Army Corps of Engineers was adopted. From the calculation, a cementitious blend of 110 – 175 kg/m^3, containing 67% cement and 33% fly ash, sufficient to meet 7 – 15 MPa in 28 days. Although 110 kg/m^3 is sufficient, 150 kg/m^3 (as middle value) and 175 kg/m^3 (as upper value) of cementitious was prepared as a “safety factor” to consider a decrease of compressive strength in on-site trials due to the differences of compaction method and other construction factor.

The optimal gravel-to-sand ratio was determined through laboratory-scale testing using three variations: 40/60, 60/40, and 50/50, with a cementitious content of 150 kg/m^3. These ratios were selected based on typical values recommended by the US Army Corps of Engineers for estimating RCC trial mixture proportions. The most suitable ratio identified from the laboratory tests will be applied at the on-site scale to ensure consistency and performance. Consequently, all mix designs incorporating three different cementitious contents are presented in Table 3.

3.3 Specimen Preparation

3.3.1 *Laboratory trials*

Laboratory trials were conducted using a pan mixer and a vibrating hammer for compaction at 2000 ± 200 impacts/min according to ASTM C1435 to form a cylindrical specimen with 150 mm diameter and 300 mm height for all RCC mixtures [10]. The specimens were removed from the molds 24 hours after casting and cured in water.

3.3.2 *On-site trials*

RCC was placed with dimensions of 10 meters in length and 3 meters in width. On-site trials were conducted using a twin-shaft mixer. The vibratory roller used for compaction weighs 10 tons and operates at vibrations ranging from 1730 to 2000 vibrations per minute. Four to six roller passes (a round trip with a double-drum roller across the same area constitutes two passes) are adequate to achieve desired densities for RCC lifts of 150- to 300-mm (6- to 12-in.) thickness (U.S. Army Corps of Engineer). In this experiment, eight passes of compaction were executed considering the vibratory roller used was a single-drum roller. The compaction was to be completed within 15 min after spreading and within 45 min from the time of initial mixing. Thermocouples are embedded within the RCC to continuously monitor the internal temperature. Cores were drilled from the RCC mock-up at 7, 28, and 90 days of age. For each batch of mixing, a portion of the RCC is taken and formed into cylinder using vibrating hammer as a specimen to evaluate the performance of the twin shaft wet mixer.

3.4 Specimen Testing

During every RCC production, the testing of slump and vebe time is performed in accordance with ASTM C143 [11] and ASTM C1170 [12]. The compressive strength tests followed the procedure of ASTM C39 [13]. The load was applied according to this standard with a loading rate of 0.25 ± 0.05 MPa/s and the failure load was recorded. The specimens were tested at 7, 28, 90, and 150 days of age.

3.5 Core Drill

A 4 in. core was extracted from the mock-up RCC in the on-site trials according to ASTM C42/C42M [14]. No damage or cracking was found along the specimens in each layer of RCC. Therefore, core RCC specimens can be used to evaluate both its physical and mechanical properties. The compressive strength of core specimens was tested at 7, 28, and 90 days of age. The core specimens will serve as the reference specimens for those prepared in the laboratory trials.

4. RESULTS AND DISCUSSION

4.1 Optimum Fraction of Gravel/Sand

The gravel/sand fraction is considered optimal when the RCC achieves maximum compressive strength. Fig.2 shows that the maximum compressive strength of RCC is achieved when 50/50 fraction of gravel/sand is used. It indicates that using a 50/50 gravel/sand ratio results in a well-structured mix. The sand effectively fills the voids formed by the coarse aggregate matrix, leading to minimal porosity and a dense RCC. Conversely, the strength of concrete reduces when larger coarse aggregates are used, as they create more voids in the concrete, leading to an increase in pore volume [15].

As shown in Fig.3, the test specimens with a 50/50 gravel-to-sand ratio exhibited smooth, uniform surfaces with no signs of honeycombing or voids. Honeycombing, typically characterized by gaps or exposed aggregate on the surface, indicates poor compaction or improper mix proportions. The absence of honeycombing in these specimens suggests that the mix achieved optimal workability and compaction, allowing for a dense, cohesive structure. This also implies that the effective surface area of the specimen matches the total surface area of the cylinder, ensuring full contact between the concrete and the mold. This uniformity is critical for structural integrity, as it minimizes weak points and enhances the durability and strength of the concrete. The 50/50 ratio, therefore, not only improves aesthetic quality but also contributes to better mechanical performance, making it a favorable choice for RCC applications.

4.2 Optimum Moisture Content

Determining the optimum water content is crucial for achieving the maximum density of Roller Compacted Concrete (RCC), which directly impacts its strength and durability. The maximum density and corresponding optimum water content were identified by plotting measured densities against varying moisture levels in compacted specimens. The RCC mix in Table 3 contains 4% moisture, which served as the baseline.

To create the density vs. water content plot, the mix design was adjusted to 2.5%, 3.5%, 5.25%, and 6% moisture levels, allowing for a comprehensive evaluation of how different moisture contents influence the compaction process. Maximum density, which correlates with higher compressive strength, was achieved at 4% moisture, as shown in Fig. 4. This indicates that the mix design in Table 3 already reflects the optimum moisture content, ensuring both maximum density and compressive strength without further adjustments.

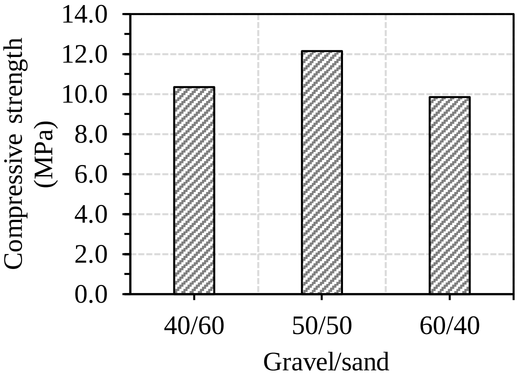

Fig.2 Gravel/sand fraction vs compressive strength

Fig.3 Visual inspection of RCC using 50/50 and 60/40 fraction of gravel/sand

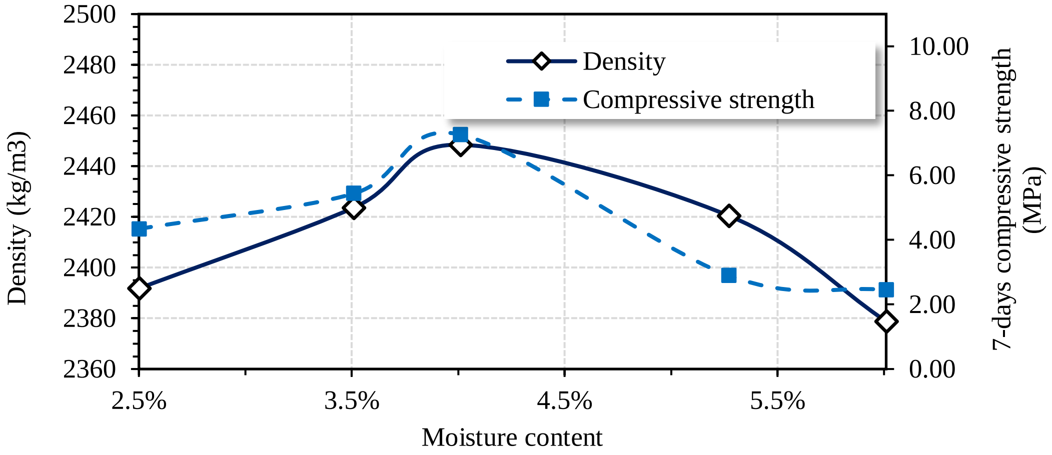

Fig.4 Moisture-density relationship (optimum moisture content)

4.3 Compressive Strength

4.3.1 *Laboratory trials*

Compressive strength of the RCC produced in laboratory are presented in Fig.5. Fig.5 shows that LCRCC using 110 kg/m^3 of cementitious successfully reaches 15 MPa at 150 days of age. Although some material properties did not meet the criteria, the available materials have proven usable because they can achieve the desired strength. A significant increase in compressive strength occurs at a later age due to the utilization of fly ash. This finding aligns with Lane and Best's (1982) study [16], which observed a 50% enhancement in concrete compressive strength at 1 year (365 days) for mixtures containing 30% Fly Ash type F, relative to their 28-day strength. The 28-days compressive strength of MCRCC using 150 kg/m^3 and 175 kg/m^3 cementitious are 15.41 MPa and 20.86 MPa, respectively as shown in Fig.6. It can be concluded that the compressive strength of RCC improves as the amount of cement per unit volume increases. Additionally, a compressive strength of 15 MPa can be achieved at 28 days using MCRCC with 150 and 175 kg/m³ cementitious content.

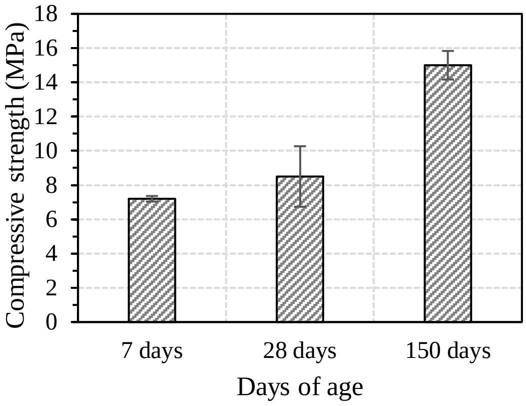

Fig.5 Compressive strength of LCRCC using 110 kg/m^3 cementitious content

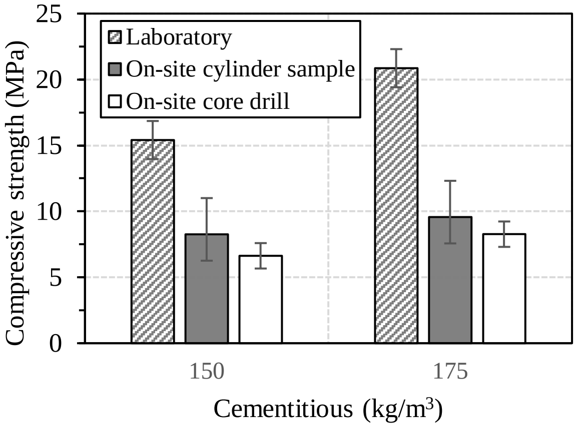

Fig.6 28-days Compressive strength of MCRCC made in laboratory and on-site trials

4.3.2 *On-site trials*

Compressive strength of the RCC produced in on-site are presented in Fig.6. The compressive strength of MCRCC cylinder specimen with 150 kg/m^3 and 175 kg/m^3 cementitious content are 8.26 MPa and 9.57 MPa, respectively. Whereas compressive strength of core drill with 150 kg/m^3 and 175 kg/m^3 cementitious content are 6.63 MPa and 8.27 MPa, respectively.

The core drill results are nearly identical to the cylinder specimen results, suggesting that the implementation method is accurate and there is no significant difference between compaction using vibrating hammer and vibratory roller. However, both the core drill and cylinder specimen results are only half of the lab-scale results, indicating that there is a decrease of compressive strength in on-site trial due to the inadequate mixing of twin shaft wet mixer.

It can be concluded that although increasing cementitious content enhances the compressive strength of RCC, uncontrolled factors in the field lead to a decrease in compressive strength. The 28-day compressive strength of LCRCC (110 kg/m³ cementitious) made in laboratory and MCRCC (150 kg/m^3 and 175 kg/m^3 cementitious) made on-site are similar. In this case, the "safety factor" considered in the addition of cementitious material (from 110 kg/m^3 to 150 kg/m^3 and 175 kg/m^3) ensures that 15 MPa is predicted to be achieved at 150 days in the field.

4.4 Density

The density and compressive strength of concrete cement paste are influenced by various factors such as the water-to-cementitious materials ratio, the inclusion of supplementary cementitious materials, the use of admixtures, curing processes, the type of cement used, etc. [17]. Density and compressive strength have a linear relationship and increase with time [18]. This behavior also appeared in this RCC experiment. Laboratory tests revealed that cylinder specimens with cementitious contents of 150 kg/m^3 and 175 kg/m^3 (MCRCC) had densities of 2333 kg/m^3 and 2328 kg/m^3, respectively. In contrast, on-site trials showed that the cylinder specimens had densities of 2269 kg/m^3 and 2296 kg/m^3 for the same cementitious contents. Additionally, core drill specimens from the on-site trials exhibited densities of 2232 kg/m^3 and 2278 kg/m^3 for cementitious contents of 150 kg/m^3 and 175 kg/m^3, respectively.

4.5 Effects of Compaction Methods

This evaluation is carried out by comparing the compressive strength and density of two types of samples obtained from the on-site trial. The first type includes core drills extracted directly from the compacted RCC surface on-site, where compaction was achieved using a vibratory roller, simulating actual field conditions. The second type consists of cylinder specimens prepared during the same on-site trial, but these were compacted using a vibrating hammer to ensure controlled and uniform compaction in a laboratory-like setting. By analyzing and comparing the results from these two methods, the evaluation aims to assess the consistency and reliability of RCC performance under field and controlled conditions.

4.5.1 *Effects of compaction methods on the density*

The degree of compaction can be measured by dividing the density obtained in on-site trials by the density achieved in the laboratory. Based on Fig.7, it was observed that the degree of compaction obtained from on-site MCRCC are 98.3% and 99.2% using 150 kg/m^3 and 175 kg/m^3 cementitious content, respectively. It suggests that vibratory roller is adequate to achieve maximum density determined from vibrating hammer. This can be attributed to their comparable operational rates, dynamic force, and frequencies.

The vibrating hammer operated at 2000 ± 200 impacts per minute with a dynamic force of 0.234 MPa, ensuring uniform compaction for smaller, controlled specimens. The vibratory roller ran at 2000 vibrations per minute with a dynamic force of 0.162 to 0.308 MPa, allowing effective compaction over larger areas and varying conditions. This highlights the precision of lab compaction versus the adaptability of field methods.

4.5.2 *Effects of compaction methods on the compressive strength*

In contrast to density, RCC compacted using vibratory rollers exhibits lower compressive strength compared to specimens compacted using vibrating hammer. Fig.6 shows that vibratory roller can only achieve 80.2% and 86.4% compressive strength of MCRCC using 150 kg/m^3 and 175 kg/m^3, respectively. The decrease up to 20% can be attributed to the difference compaction methods between vibrating hammer and vibratory roller which influence the distribution and compaction of aggregates and cement paste in RCC.

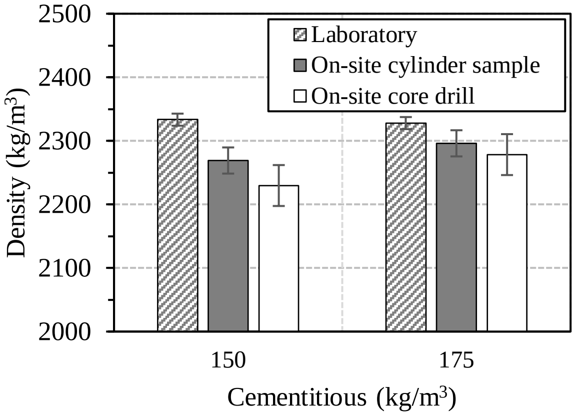

Fig.7 Density of MCRCC made in laboratory and on-site trials

Fig.8 portrays the correlation between density and compressive strength. It was found that denser concrete tends to exhibit higher strength and contains fewer voids and less porosity. This behavior was also observed in the research conducted by Iffat [18]. A slight decrease in density significantly reduces its compressive strength. Therefore, achieving a 98% - 99% degree of compaction resulted in up to a 20% decrease in compressive strength. This finding is consistent with the study by LaHucik and Roesler, which reported that a 4% reduction in field density compared to laboratory density led to a 45% reduction in the compressive strength of field specimens [3]. This reduction in compressive strength is crucial to consider when calculating the mix design for RCC dam.

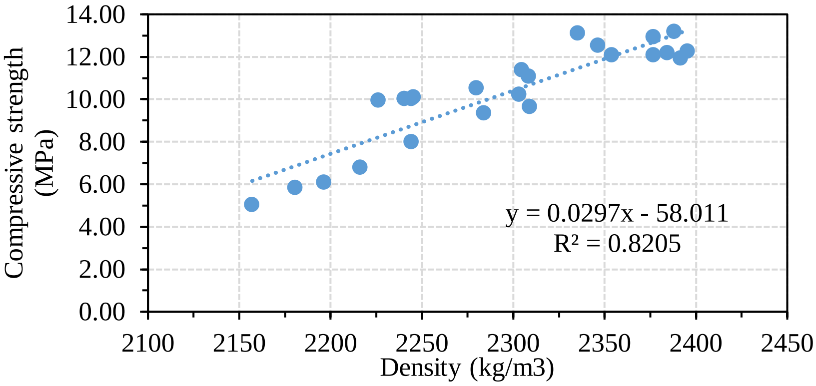

Fig.8 Compressive strength vs density of RCC using 150 kg/m^3 and 175 kg/m^3 cementitious content made in laboratory and on-site trials

4.6 Effects of Mixing Scale

The effect of mixing scale was studied by comparing the compressive strength and density of cylinder specimen made in on-site trial (mixed using twin shaft wet mixer) and cylinder specimen made in laboratory (mixed using pan mixer), both specimens were compacted using vibrating hammer according to ASTM C1435 [10].

4.6.1 *Effects of mixing scale on the density*

In Fig.7, it was found that the density correlation of cylinder specimens made in on-site and laboratory using 150 kg/m^3 and 175 kg/m^3 are 97.2% and 98.6%, respectively. This indicates that mixing scale and the consistency did not lead to a significant effect on density of RCC. Density of RCC is dependent on density of aggregates and compaction method.

4.6.2 *Effects of mixing scale on the compressive strength*

Different mixing procedures and mixer types can produce varying microstructures which lead to a different compressive strength, even for the same composition [18], [20]. Based on Fig.6, the compressive strength ratios of cylinder specimens made in on-site and laboratory using 150 kg/m^3 and 175 kg/m^3 (MCRCC) are 53.6% and 45.9%, respectively. The significant reduction in compressive strength up to 55% suggests that the large-scale mixing using twin shaft wet mixer demonstrated lower effectiveness.

This is also supported by the poor mixing results shown in Fig.9 which the aggregates were not uniformly mixed and Fig.10 which shown that the cement paste was not evenly distributed and tended to accumulate on one side, causing some segments of RCC mockup in on-site trial having low compressive strength. The coefficient of variation can be a measure of the homogeneity of the RCC produced. The lower the coefficient of variation the more homogenous mixture is obtained. Coefficient of variation is defined as the ratio of the standard deviation to the mean. The standard deviation of compressive strength represents the dispersion of compressive strength of three different MCRCC specimens in each group test.

It has been shown in Fig.6 that cylinder specimens made on-site using twin shaft wet mixer (large-scale mixing) have a higher standard deviation compared to cylinder specimens made in laboratory using pan mixer (small-scale mixing). The coefficient of variation of small-scale and large-scale mixing is 8% and 26%, respectively. It can be concluded that more homogenous mixture is obtained in laboratory trials which led to a better compressive strength compared to RCC mixed in on-site trials. This finding aligns with Dils J, De Schutter G, Boel V, who identifies the intensive mixer with a rotating pan as having the lowest coefficient of variation among all the mixers evaluated [18].

However, US Army and ICOLD suggest the use of twin- shaft mixer since it is ideal for RCC placements requiring continuous, high production rates. The concern is the mixer used in large-scale was twin-shaft wet mixer, which designed to handle wet materials, it was found that the blades and paddles may not be suited for dry mixing like RCC. Nevertheless, this mixer was chosen due to its current availability, and the results of this study have proven that the choice of mixer significantly determines the quality of RCC. Dry mixer should be used because it blades and paddles designed to ensure even distribution of granular materials and promote efficient material flow.

A small batch size mixer used in laboratory cannot be used in actual RCC dam construction since it is a large-scale production, so it is necessary to transfer a mix into a factory-based production. This transition will require significant alterations to the original mix design, since it was found on this study that there is a significant effect of mixing scale on the compressive strength of RCC.

Fig.9 The cement paste was not evenly distributed and tended to accumulate on one side

Fig.10 The aggregate, cement, and fly ash were not uniformly mixed during large-scale mixing

5. CONCLUSIONS

This investigation compared laboratory and on-site trials by evaluating mix design, effects of compaction methods, and effects of mixing scale on the density and compressive strength of RCC. The major results are summarized as follows:

(1) The maximum compressive strength and density was achieved with the use of 50/50 gravel/sand ratio and 4% moisture content. It results in a well-structured mix. The sand effectively fills the voids formed by the coarse aggregate matrix, leading to minimal porosity and a dense RCC.

(2) The targeted compressive strength of 15 MPa was successfully reached at 150 days of age with LCRCC using 110 kg/m^3 of cementitious and at 28 days of age with MCRCC using 150 kg/m^3 and 175 kg/m^3 of cementitious.

(3) The 28-day compressive strength of LCRCC using 110 kg/m³ cementitious material made in the laboratory is comparable to MCRCC using 150 kg/m³ and 175 kg/m³ cementitious materials made on-site. This demonstrates that the additional cementitious material in the on-site mixes (from 110 kg/m³ to 150 kg/m³ and 175 kg/m³) is expected to provide a sufficient safety margin, ensuring that a compressive strength of 15 MPa can be achieved at 150 days in practical applications.

(4) The density of MCRCC compacted using a vibratory roller achieved a higher degree of compaction, reaching 98.3% and 99.2% with 150 kg/m3 and 175 kg/m3 cementitious content, respectively. The density of MCRCC was not affected by the mixing scale, as the correlation of cylinder specimens made on-site and in the laboratory was 97.2% and 98.6%, using 150 kg/m3 and 175 kg/m3 respectively.

(5) The compressive strength of RCC compacted using a vibratory roller can only achieve 80.2% and 86.4% of the compressive strength obtained in RCC compacted using a vibrating hammer.

(6) From the comparison of density and compressive strength, it was found that a slight decrease in density by about 1% - 2% significantly reduces its compressive strength by up to 20%. This is due to the different compaction methods between the vibrating hammer and the vibratory roller, which influence the distribution and compaction of aggregates and cement paste in RCC.

(7) A strength reduction was also found in the large-scale mixing, with reductions of 46.4% and 54.1% for MCRCC using 150 kg/m³ and 175 kg/m³ cementitious content, respectively. This is due to the inadequate mixing, where the aggregate, cement, and fly ash were not uniformly mixed.

(8) The study confirms that the choice of mixer significantly impacts RCC quality. While a wet twin-shaft mixer was used due to availability, its design is unsuitable for RCC’s dry mixing process. A dry twin-shaft mixer is recommended for future applications to ensure uniform material distribution and optimal mix consistency.

(9) Since large-scale mixing demonstrates lower effectiveness, it is necessary to transition the mix to a factory-based production system, which will involve substantial modifications to the mix design to ensure consistency, quality control, and optimal performance in large-scale applications.

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7. REFERENCES

[1] ICOLD Committee on Concrete Dams. Roller-Compacted Concrete Dams, 1st ed. CRC Press, 2020, pp. 1-426.

[2] Şengün E, Alam B, Shabani R, Yaman IO. The effects of compaction methods and mix parameters on the properties of roller compacted concrete mixtures. Construction and Building Materials, Vol. 228, 2019, 116807.

[3] LaHucik J, Roesler J. Field and laboratory properties of roller-compacted concrete pavements. Transportation Research Record, Vol. 2630, Issue 1, 2017, pp. 33-40.

[4] ACI Committee 207, Roller Compacted Mass Concrete, American Concrete Institute, ACI 207.5R-89, Reapproved 1997.

[5] Abu-Khashaba MI, Adam I, El-Ashaal A. Investigating the possibility of constructing low cost roller compacted concrete dam. Alexandria Engineering Journal, Vol. 53, Issue 1, 2014, pp. 131-142.

[6] ASTM, ASTM C150/C150M-21: Standard Specification for Portland Cement, ASTM International, Vol. D3699, Issue 19, 2021.

[7] Kalina RD, Al-Shmaisani S, Ferron RD, Juenger MC. False positives in ASTM C618 specifications for natural pozzolans. ACI Materials Journal, Vol. 116, Issue 1, 2019, pp. 165-172.

[8] ASTM International, ASTM C33/ C33M-16 Standard Specification for Concrete Aggregates, Vol. I, No. C, 2016.

[9] Dehghan A, Maher ML, Navarra M. The Effects of Aggregate Properties on Concrete Mix Design and Behaviour. InCanadian Society of Civil Engineering Annual Conference, Vol. 248, 2021, pp. 457-468.

[10] ASTM, ASTM C1435/C1435M − 20: Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer, 2020.

[11] ASTM, ASTM C143/C143M-12 Standard Test Method for Slump of Hydraulic-Cement Concrete, Annual Book of ASTM Standards, 2015.

[12] ASTM C1170/C1170M - 14, ASTM C1170, Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table, ASTM International, Vol. 91, No. Reapproved 1998, 2014.

[13] American Society for Testing and Materials, ASTM C39/C39M: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, Vol. 4, 2001.

[14] ASTM, ASTM C42/C42M-20: Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete, 2020.

[15] Ramdani Y., Azizah N., and Herlina N., The Effect Of Different Concrete Mix Designs And Maximum Aggregate Size Variations On The Compressive Strength of Normal Concrete. International Journal of GEOMATE, Vol. 26, No. 118, 2024, pp. 87–95.

[16] Best JF. Properties And Use of Fly Ash In Portland Cement Concrete. Concrete International, Vol. 4, Issue 7, 1982, pp. 81-92.

[17] Rasa E., Ketabchi H., and Afshar M. H. Predicting density and compressive strength of concrete cement paste containing silica fume using Artificial Neural Networks. Scientia Iranica, Vol. 16, Issue 1 A, 2009, pp. 33-42.

[18] Iffat S. Relation between density and compressive strength of hardened concrete. Concrete Research Letters, Vol. 6, Issue 4, 2015, pp. 182-189.

[19] Dils J, De Schutter G, Boel V. Influence of mixing procedure and mixer type on fresh and hardened properties of concrete: a review. Materials and structures, Vol. 45, Issue 11, 2012, pp. 1673-1683.

[20] Ozolins E, Zavickis J, Lukasenoks A, Macanovskis A. Effect of mixer type on fresh and hardened properties of ultra-high-performance concrete (UHPC). InEngineering for Rural Development. Proceedings of the International Scientific Conference (Latvia), Vol. 20, 2021, pp. 1617-1626.