Application of the Modified Andreasen Packing Model for Optimizing Strength and Cost of Normal Concrete with Uniformly Graded Aggregates

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Abstract

Application of The Modified Andreasen Packing Model For Optimizing Strength and Cost of Normal Concrete With Uniformly Graded Aggregates. Concrete containing uniformly graded coarse aggregates generally exhibits low packing density and high porosity, which adversely affect compressive strength. Despite these limitations, such aggregate conditions are often unavoidable in practice due to material availability constraints, necessitating optimized mix design approaches to enhance mechanical performance and cost efficiency. This study aims to optimize the mix design of normal concrete with uniformly graded coarse aggregates based on SNI 03-2834-2000 using the Modified Andreasen Packing Model (MAPM), with emphasis on compressive strength and material cost evaluation. A total of 18 cylindrical specimens were tested at curing ages of 3, 14, and 28 days, with a target compressive strength of 20 MPa. At 3 days, compressive strengths of 8.10 MPa and 8.93 MPa were obtained for the SNI and MAPM methods, respectively. At 14 days, the SNI method achieved 15.48 MPa, while MAPM reached 26.90 MPa. At 28 days, the SNI method produced 19.37 MPa, whereas MAPM achieved 30.96 MPa, exceeding the target strength. In terms of material cost, the SNI method required IDR 704,212, while MAPM required IDR 675,256, resulting in a cost reduction of IDR 28,956. These findings demonstrate that MAPM significantly enhances compressive strength while reducing material costs under non-ideal aggregate conditions.

Keywords: *compressive strength, cost efficiency, Modified Andreasen Packing Model, normal concrete, uniformly graded aggregates*

INTRODUCTION

Concrete is one of the most widely used materials in infrastructure development. Its application in construction projects plays a crucial role, particularly in terms of strength performance and cost efficiency. According to the Kementerian Pekerjaan Umum (2013), concrete accounts for more than 60% of construction materials, ranging from simple structures to highly complex engineering projects. Therefore, careful attention must be given to concrete mix design, as the selection of aggregates and mixture proportions significantly influences the physical and mechanical properties of concrete (Hermawati, 2023).

In practice, concrete often contains voids or pores caused by poor particle packing, especially when aggregates exhibit a uniform gradation (uniformly graded). In such conditions, the absence of a well-distributed particle size range results in unfilled gaps between particles, leading to weak inter-particle bonding. This phenomenon increases the likelihood of aggregate segregation and high porosity, both of which negatively affect concrete strength (Mulyati & Alluhri, 2016). Consequently, low-quality concrete tends to have insufficient compressive strength, making it more susceptible to early deterioration and structural damage. This not only compromises structural performance but also leads to increased maintenance and repair costs. Furthermore, improper mix design can result in inefficient material usage, further escalating construction expenses. Therefore, achieving an optimal balance between strength and cost requires the application of precise and innovative mix design methods.

In Indonesia, standard procedures for normal concrete mix design are governed by SNI 7656:2012 and SNI 03-2834-2000. These standards provide guidelines for determining material composition and mix proportions to meet construction requirements (SNI 03-2834-2000, 2000). However, previous studies have shown that the SNI 03-2834-2000 method tends to produce concrete mixtures with higher cement content but relatively lower compressive strength, resulting in less economical designs (Alkhaly, 2018).

To improve the efficiency of concrete mix design, several innovative approaches have been introduced. One such method is the Modified Andreasen Packing Model (MAPM), which is based on particle packing theory. This method aims to optimize the distribution of aggregate particles to achieve higher packing density, thereby enhancing concrete strength while reducing cement usage. The implementation of MAPM is often supported by software such as Elkem Materials Mixture Analyser (EMMA), which facilitates the optimization of particle size distribution in concrete mixtures. Previous studies have demonstrated that MAPM can produce concrete with lower cement content and higher compressive strength across a range of target strengths (15–40 MPa at 28 days) compared to the SNI method (Alkhaly, 2018).

However, most existing studies have primarily focused on the application of MAPM to well-graded aggregates, while research on its application to uniformly graded aggregates remains limited. In addition, few studies have simultaneously evaluated both compressive strength performance and cost efficiency under such non-ideal aggregate conditions. This study focuses on the SNI method as a widely adopted national standard in Indonesia, ensuring that the findings are locally applicable. International standards such as ACI and BS are not included as comparative methods in order to maintain the focus on evaluating improvements from a conventional approach (SNI) to an innovative method (MAPM). Therefore, this study aims to conduct a comparative analysis of normal concrete mixtures with uniformly graded coarse aggregates designed using SNI 03-2834-2000 and the Modified Andreasen Packing Model (MAPM), with particular emphasis on compressive strength and cost efficiency. The optimization is achieved through appropriate mix proportioning using both methods. It is expected that this study will provide valuable insights for selecting optimal concrete mix design methods in terms of both economic feasibility and construction quality.

Aggregate Gradation Types in Concrete Mixtures

Aggregate gradation, or particle size distribution, refers to the distribution of aggregate particle sizes within a concrete mixture (Bangki, 2020). It is determined through sieve analysis, which measures the percentage of aggregates retained or passing through each sieve size. Aggregate gradation plays a critical role in influencing the packing density, workability, and overall performance of concrete. Several types of aggregate gradation are commonly identified in concrete mixtures, as illustrated in Figure 1.

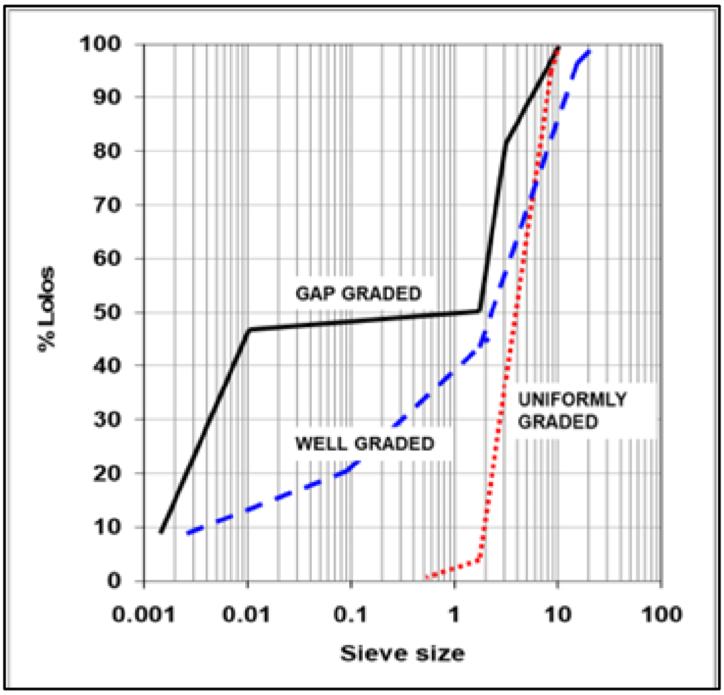


Figure 1. Types of Aggregate Gradation Curves (Ibrahim, 2021).

1. Well-Graded Aggregates (Continuous Gradation)
   Well-graded aggregates exhibit a broad and continuous distribution of particle sizes, allowing smaller particles to fill the voids between larger ones. This results in lower porosity and higher packing density, enabling optimal interlocking between particles. Consequently, well-graded aggregates are widely used in concrete mixtures due to their ability to enhance strength and durability. According to Bangki (2020), well-graded aggregates provide better performance compared to uniformly graded and gap-graded aggregates.

2. Uniformly Graded Aggregates (Single-Sized Gradation)
   Uniformly graded aggregates consist of particles with nearly the same size, resulting in a narrow range of particle distribution. In gradation curves, this condition is typically represented by a steep or nearly vertical line. Due to the lack of smaller particles to fill the voids, this type of gradation tends to have higher porosity and lower packing density. Uniformly graded aggregates are commonly used in specialized applications, such as no-fines concrete or lightweight concrete, and may also serve as a component in gap-graded mixtures.

3. Gap-Graded Aggregates (Discontinuous Gradation)
   Gap-graded aggregates are characterized by the absence of one or more intermediate particle sizes within a given sieve range. As a result, the gradation curve typically shows a horizontal segment, indicating missing fractions. This type of gradation can improve workability and reduce segregation in certain cases; however, it may also lead to inconsistent packing if not properly designed.

Compressive Strength of Concrete

Compressive strength is a fundamental property used to evaluate the mechanical performance of concrete by applying a compressive load to a test specimen until failure occurs. In general, concrete quality refers to its ability to withstand applied loads and stresses without experiencing structural damage. According to SNI 1974:2023, compressive strength is defined as the maximum load per unit area that causes a concrete specimen to fail under a compressive force applied by a testing machine.

The compressive strength of concrete, based on SNI 1974:2023, is calculated using Equation (1):

$$f_c' = \frac{P}{A} \tag{1}$$

where f_c' is the compressive strength of concrete (MPa), P is the maximum applied load (N), and A is the cross-sectional area of the specimen (mm²).

Material Cost

The production cost of concrete refers to the expenses incurred in processing raw materials into ready-to-use concrete. In construction practice, the calculation of production cost, often referred to as the cost of goods produced, is essential as it provides detailed information on the total expenses required for construction activities (Fardila & Sugian, 2023).

In Indonesia, cost estimation is commonly based on the Analisa Harga Satuan Pekerjaan (AHSP), which is a method used to determine unit costs for construction work. This method calculates total cost by combining material requirements, labor wages, and equipment usage with their respective unit prices (Melani, 2021).

The calculation of material cost in this study refers to AHSP Banyuwangi 2024, as expressed in Equation (2):

$$Cost = QTY \times Unit\ Price \tag{2}$$

where *Cost* represents the total material cost, *QTY* is the quantity of material (kg), and *Unit Price* is the cost per unit of material.

METHODS

This study employed an experimental approach conducted at the Material Testing Laboratory of Politeknik Negeri Banyuwangi. The objective was to evaluate the compressive strength and material cost of concrete through testing cylindrical specimens. The research procedure consisted of the following stages:

1. Literature Review
   The initial stage involved a comprehensive literature review to understand normal concrete mix design based on SNI 03-2834-2000 and the application of the Modified Andreasen Packing Model (MAPM) in terms of strength and cost performance. References were obtained from books, scientific journals, standards, and previous studies, particularly SNI 03-2834-2000 and research conducted by Alkhaly (2018).

2. Materials and Equipment Preparation
   The materials used in this study included Type I Portland cement (Tiga Roda brand), fine aggregate (Lumajang sand), and coarse aggregate supplied by PT. Merak Jaya Beton Plant. Water used for mixing was obtained from Politeknik Negeri Banyuwangi. All equipment utilized in this study was sourced from the Material Testing Laboratory of the Civil Engineering Department.

3. Material Characterization Tests
   Material characterization tests were conducted to determine the physical properties of materials and to ensure their compliance with applicable standards. The concrete mixture consisted of Portland cement, fine aggregate, coarse aggregate, and water. The following tests were performed:

a. Cement
   1) Specific gravity (ASTM C188-95 (2003), MOD)
   2) Bulk density (ASTM C188-89)

b. Fine and Coarse Aggregates
   1) Specific gravity (ASTM C128-78)
   2) Water absorption (ASTM C128)
   3) Bulk density (ASTM C29-78)
   4) Moisture content (ASTM C556-72)
   5) Silt content (ASTM C117-76)
   6) Sieve analysis (SNI 03-2834-2000)

4. Mix Design Proportioning
   a. Mix Design Based on SNI 03-2834-2000
   The mix design followed SNI 03-2834-2000 to achieve a target compressive strength of 20 MPa at 28 days. The procedure included determining target strength, standard deviation, margin, type of cement and aggregates, water–cement ratio (0.60), slump range (7.5–15 cm), maximum aggregate size (20 mm, uniformly graded), free water content, aggregate gradation, proportion of fine and coarse aggregates, relative density, unit weight of concrete, combined aggregate content, and final mix correction based on moisture conditions.

   b. Optimization Using the Modified Andreasen Packing Model (MAPM)
   The MAPM approach was applied to optimize particle size distribution and maximize packing density using Elkem Materials Mixture Analyser (EMMA). The procedure involved inputting material data (cement, sand, gravel, and water), setting the distribution modulus parameter (q = 0.35), defining maximum aggregate size, and generating optimized mix proportions. The resulting particle size distribution curves and packing density were analyzed to determine the optimal mix. The selected q-value (0.35) is widely used for normal concrete and is considered optimal for achieving a balance between packing density and workability (Karimi & Brouwers, 2023).

5. Specimen Preparation, Curing, and Compressive Strength Testing
   Concrete specimens in the form of cylinders were prepared using a concrete mixer. The specimens were cured in water for 7, 14, and 28 days. Compressive strength tests were conducted using a compressive testing machine (CTM) in accordance with standard procedures.

6. Statistical Analysis
   Statistical analysis was performed by calculating the Coefficient of Variation (CoV) in accordance with SNI 1974:2023. This analysis was used to evaluate the variability and consistency of the test results.

7. Material Cost Analysis
   Material cost analysis was conducted to evaluate the cost efficiency of each concrete mixture. The calculation was based on AHSP Banyuwangi 2024 to determine total material requirements and associated costs.

RESULT AND DISCUSSION

The results of this study include material characterization tests, mix design proportioning, material quantity calculations, compressive strength evaluation, and material cost analysis.

1. Material Characterization Test Results

The results of material characterization tests for cement, fine aggregates, and coarse aggregates generally met the specified requirements, except for the moisture content of the fine aggregate. The moisture content exceeded the standard limits due to the damp condition of the aggregates, which was influenced by weather conditions at the time of testing. A summary of the material characterization results used for concrete specimen preparation is presented in Table 1.

Table 1. Summary of Cement Characteristics

No.	Test Parameter	Result	
1	Specific Gravity	3.02	
2	Bulk Density	With Rodding 1.15 gr/cm^3	Without Rodding 1.27 gr/cm^3

The results of the fine aggregate (sand) characterization tests are presented in Table 2.

Table 2. Summary of Fine Aggregate Characteristics

No.	Test Parameter	Result
1	Specific Gravity	2.59
2	Water Absorption	3.66%

3	Bulk Density	With Rodding 1.69 gr/cm^3	Without Rodding 1.55 gr/cm^3
4	Moisture Content	4.97%	
5	Silt Content	4.60%	
6	Sieve Analysis	FM = 2.48 (Zone II)	

Based on the sieve analysis results, the fine aggregate gradation with a fineness modulus (FM) of 2.48 falls within the upper and lower limits of Zone II, as illustrated in Figure 2.

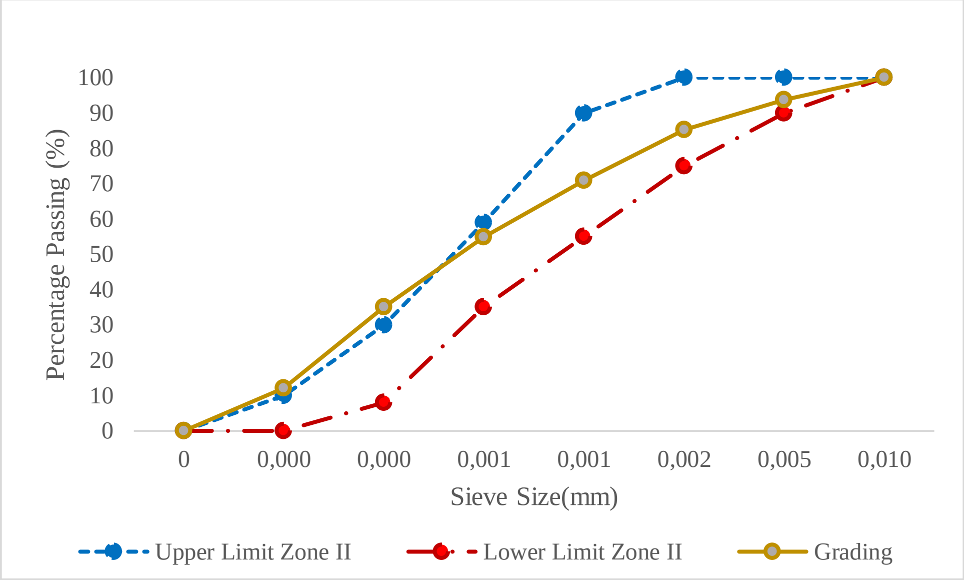


Figure 2. Sieve Analysis Curve of Fine Aggregate (Zone II)

The results of the coarse aggregate (gravel) characterization tests are presented in Table 3.

Table 3. Summary of Coarse Aggregate Characteristics

No.	Test Parameter	Result	
1	Specific Gravity	2.47	
2	Water Absorption	2.15%	
3	Bulk Density	With Rodding 1.29 gr/cm^3	Without Rodding 1.21 gr/cm^3
4	Moisture Content	0.17%	
5	Silt Content	0.47%	
6	Sieve Analysis	FM = 6.90	
7	Aggregate Type	*Uniformly-graded*	

Based on the sieve analysis results with a maximum coarse aggregate size of 20 mm, as shown in Figure 3, the aggregate gradation does not fall within the specified upper and lower limits. This indicates the presence of gaps in the particle size distribution, classifying the aggregate as uniformly graded. Specifically, 91.06% of particles were retained on the 9.5 mm sieve, 8.53% on the 4.75 mm sieve, 0.21% on the 2.36 mm sieve, and 0.19% on smaller sieve sizes. This distribution shows that most particles fall outside the recommended gradation limits, resulting in a narrow particle size range and confirming the uniformly graded condition.

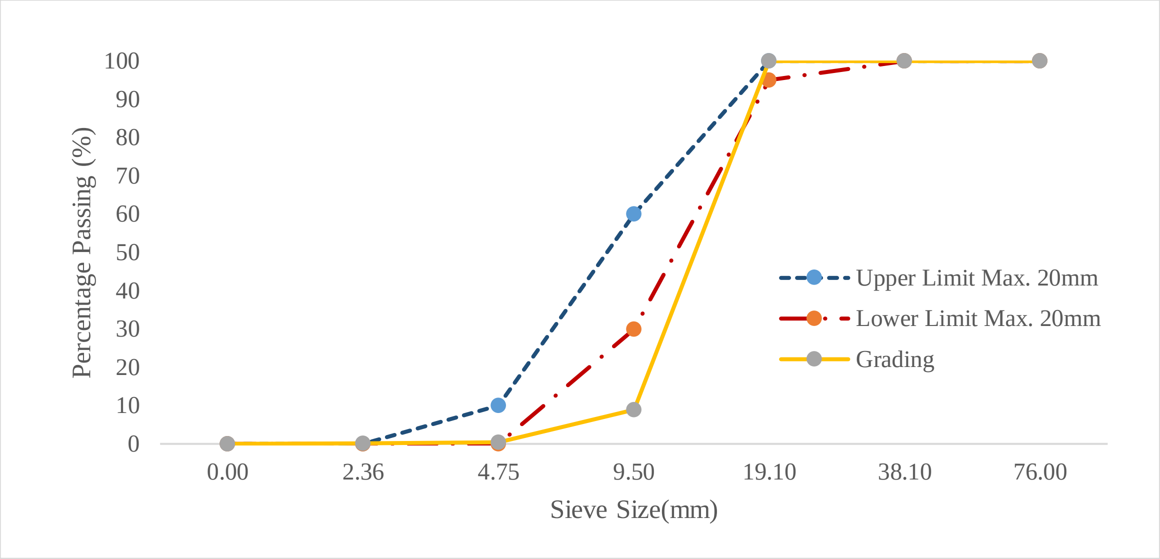


Figure 3. Sieve Analysis Curve of Coarse Aggregate (Maximum Size 20 mm)

2. **Concrete Mix Design Proportioning**

The mix proportions calculated using the SNI 03-2834-2000 method and optimized using the Modified Andreasen Packing Model (MAPM) are presented as follows:

a. Mix Design Based on SNI Method

The normal concrete mix design based on SNI 03-2834-2000 was calculated using the Job Mix Formula (JMF). The resulting mix proportions are shown in Table 4.

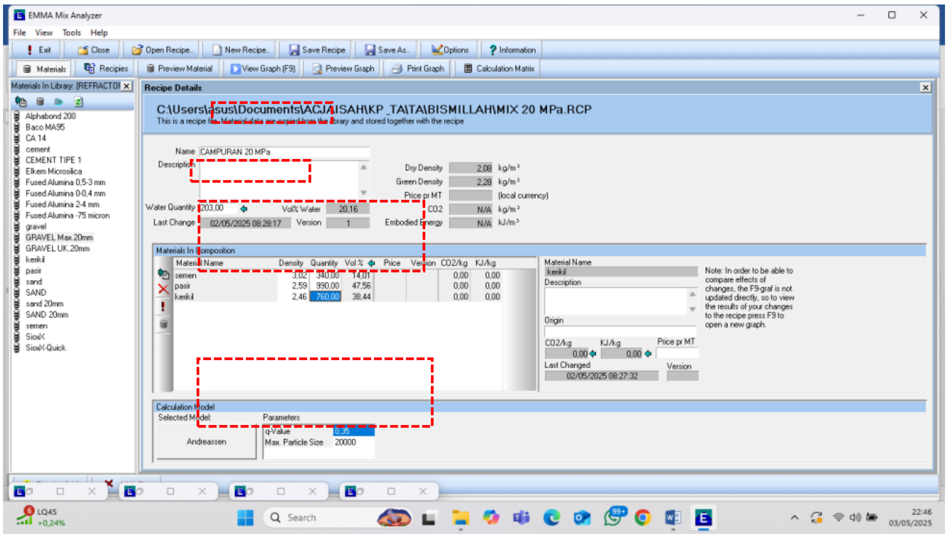
Table 4. Mix Proportions Based on SNI Method

Mix Proportion (per m³)	Cement (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)
	364.77	204.67	745.03	955.43

b. Mix Design Optimization Using MAPM

The optimization of the concrete mix design using the Modified Andreasen Packing Model (MAPM) was carried out with the assistance of Elkem Materials Mixture Analyser (EMMA). The optimization process includes the following steps:

1) Inputting the initial mix proportions (cement, water, sand, and gravel), defining the distribution modulus parameter (q = 0.35), and setting the maximum aggregate size to 20 mm.



C:\Users\asus\Documents\ACJAISAH\KP_TA\TA\BISMILLAH\MIX 20 MPa.RCP

This is a recipe file. Material data are copied from the library and stored together with the recipe

Name: CAMPURAN 20 MPa

Description:

Water Quantity: 203,00 | Vol% Water: 20,16

Last Change: 02/05/2025 08:28:17 | Version: 1

Dry Density: 2,08 kg/m³

Green Density: 2,28 kg/m³

Price pr MT: (local currency)

CO2: N/A kg/m³

Embodied Energy: N/A kJ/m³

Materials In Composition

Material Name	Density	Quantity	Vol %	Price	Version	CO2/kg	KJ/kg
semen	3,02	340,00	14,01			0,00	0,00
pasir	2,59	990,00	47,56			0,00	0,00
kerikil	2,46	760,00	38,44			0,00	0,00

Material Name: kerikil

Description:

Origin:

CO2/kg: 0,00 | KJ/kg: 0,00 | Price pr MT:

Last Changed: 02/05/2025 08:27:32 | Version:

Note: In order to be able to compare effects of changes, the F9-graf is not updated directly, so to view the results of your changes to the recipe press F9 to open a new graph.

Calculation Model

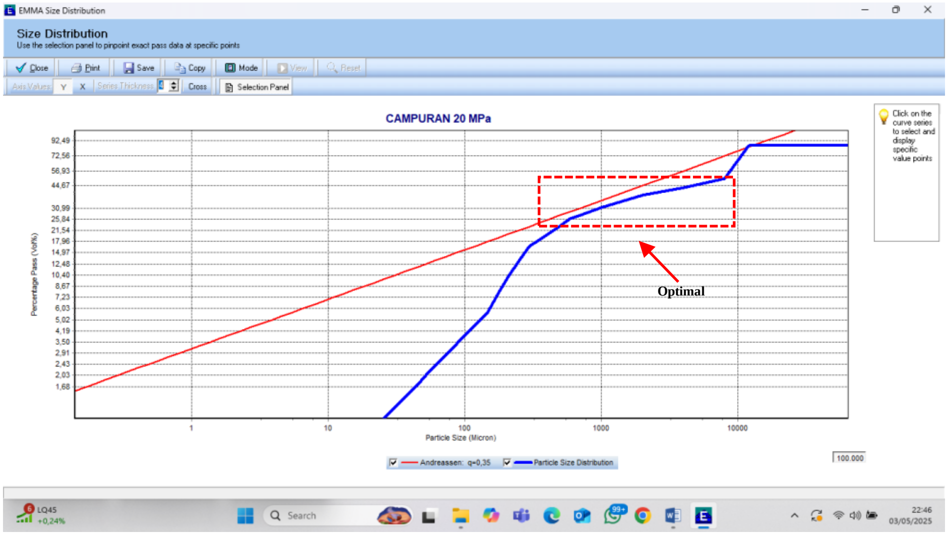
Selected Model: Andreassen

Parameters: q-Value 0,35; Max. Particle Size 20000

Figure 4. Input of Material Proportions in EMMA Software

2) The optimal mix proportion is determined by comparing the mixture curve with the target packing curve. If the mixture curve lies significantly below the optimal curve, the aggregate content should be increased and the distribution modulus (q) adjusted. Conversely, if the mixture curve is above the optimal curve, the aggregate content should be reduced.

3) The optimization process is repeated iteratively until the optimal aggregate composition is achieved, as illustrated in Figure 5.



Use the selection panel to pinpoint exact pass data at specific points

Click on the curve series to select and display specific value points

Figure 5. Optimized Particle Size Distribution Curve Using MAPM

The optimized mix proportions obtained using the Modified Andreasen Packing Model (MAPM) are presented in Table 5.

Table 5. Mix Proportions Based on MAPM

Mix Proportion (per m³)	Cement (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)
	340	203	990	760

A comparison of mix proportions between the SNI 03-2834-2000 method and the MAPM optimization is shown in Table 6.

Table 6. Comparison of Mix Proportions

Method	Cement (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)
SNI	1	0.56	2.04	2.62
MAPM	1	0.59	2.91	2.23

The implementation of MAPM in practice requires the use of Elkem Materials Mixture Analyser (EMMA), which is not yet widely adopted. However, the approach can still be adapted through simplified aggregate gradation methods.

3. Compressive Strength Results

The compressive strength test was conducted on cylindrical specimens with a diameter of 150 mm and a height of 300 mm, targeting a design strength of 20 MPa. Tests were performed at curing ages of 3, 14, and 28 days, with three specimens for each method at each age. The test results are presented in Table 7.

Table 7. Compressive Strength Test Results

Method	Age (days)	Weight (kg)	Diameter (mm)	Height (mm)	Max Load (kN)
SNI	3	12.32	150	300	138.02
	3	12.17	150	300	150.01

Method	**Age (days)**	**Weight (kg)**	**Diameter (mm)**	**Height (mm)**	**Max Load (kN)**
	3	12.16	150	300	141.63
	14	11.94	150	300	287.05
	14	11.87	150	300	267.55
	14	11.90	150	300	266.16
	28	12.19	150	300	316.36
	28	12.34	150	300	352.49
	28	12.18	150	300	357.93
MAPM	3	12.28	150	300	165.31
	3	12.31	150	300	154.22
	3	12.39	150	300	153.69
	14	12.33	150	300	462.67
	14	12.21	150	300	496.12
	14	12.24	150	300	466.26
	28	12.33	150	300	579.80
	28	12.25	150	300	502.64
	28	12.23	150	300	558.91

Based on the calculation results, the compressive strength values are illustrated in Figure 6.

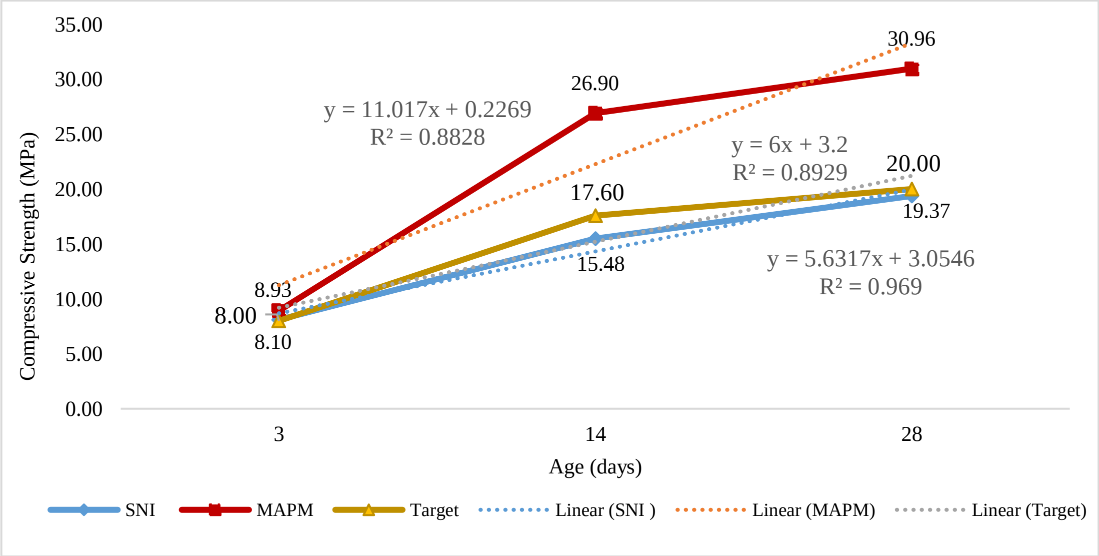


Figure 6. Compressive Strength Development of Concrete

The results show that under uniformly graded aggregate conditions, the SNI method achieved compressive strengths of 8.10 MPa (3 days), 15.48 MPa (14 days), and 19.37 MPa (28 days). In contrast, the MAPM method produced higher strengths of 8.93 MPa, 26.90 MPa, and 30.96 MPa at the same curing ages. The Coefficient of Variation (CoV) values for both methods were relatively low, indicating good consistency of test results. The SNI method showed CoV values of 1.58%, 1.64%, and 2.52%, while MAPM showed 1.60%, 1.71%, and 0.78% for 3, 14, and 28 days, respectively. These values fall within acceptable quality control limits.

Trendline analysis indicates a strong positive linear relationship between curing age and compressive strength. The MAPM method exhibited the highest slope (approximately 11.017), indicating a faster rate of strength development. The coefficient of determination ($R^2 \geq 0.88$) confirms a strong correlation between variables. Compared to the target strength, MAPM significantly exceeded the design value at 14 and 28 days, while the SNI method remained slightly below the target at later ages. Overall, these findings demonstrate that MAPM provides a more effective and consistent improvement in compressive strength.

4. Material Cost Analysis

The material cost calculation, based on AHSP Banyuwangi 2024, indicates that the MAPM method is more economical than the SNI method, with a cost difference of IDR 28,956. This reduction occurs because the SNI method requires higher amounts of cement, water, and coarse aggregate, while using less fine aggregate. In contrast, the MAPM method requires lower amounts of cement, water, and coarse aggregate, but a higher amount of fine aggregate. The material cost calculation for the concrete mix proportions using the SNI and MAPM methods is presented in Table 8.

Table 8. Material Cost per m³

Method	Material	Quantity	Unit	Unit Proce	Total Cost
SNI	Cement	364.77	kg	Rp1,267	Rp462,038
	Fine Aggregate	745.03	kg	Rp130	Rp96,984
	Coarse Aggregate	955.43	kg	Rp150	Rp143,685
	Water	214.67	kg	Rp7	Rp1,503
				Total Cost	Rp704,212
MAPM	Cement	340.00	kg	Rp1,267	Rp430,664
	Fine Aggregate	990.00	kg	Rp130	Rp128,876
	Coarse Aggregate	760.00	kg	Rp150	Rp114,295
	Water	203.00	kg	Rp7	Rp1,421
				Total Cost	Rp675,256

5. Comparison of Compressive Strength and Cost Material

A comparison of compressive strength and material cost between the SNI and MAPM methods is presented in Table 9.

Table 9. Comparison of Strength and Cost

Method	Age (days)	Compressive Strength (MPa)	Cost
SNI	3	8.10	Rp704,212
	14	15.48	
	28	19.37	
MAPM	3	8.93	Rp675,256
	14	26.90	
	28	30.96	

CONCLUSION

This study demonstrates that the application of the Modified Andreasen Packing Model (MAPM) significantly improves the performance of normal concrete with uniformly graded aggregates. At 28 days, MAPM achieved a compressive strength of 30.96 MPa, compared to 19.37 MPa for the SNI method, representing an increase of approximately 59.6% . In addition, the MAPM method reduced material cost by IDR 28,956, indicating better cost efficiency. These findings confirm that MAPM provides a more optimal balance between strength and cost compared to the conventional SNI method. However, this study has several limitations, including a relatively small number of specimens (18 samples) and the absence of advanced statistical analysis.

RECOMMENDATIONS

Future studies are recommended to:

1. Investigate different aggregate gradation zones (Zone I–IV)
2. Compare various coarse aggregate conditions (well-graded, uniformly graded, and gap-graded)
3. Apply larger sample sizes and advanced statistical methods

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