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Optimizing ceramic waste content in concrete mix design: model development and android application

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Abstract
There is an increasing need for practical tools that help users determine the appropriate mix composition of concrete incorporating ceramic waste as a partial fine aggregate replacement. Such tools can simplify the process of designing environmentally friendly concrete while ensuring that the resulting material meets the required strength standards. This study aims to determine the percentage of concrete mixture utilizing ceramic waste as a substitute for fine aggregates in concrete, assess its impact on concrete compressive strength using the RMSE method, and visualize it through Android modulator technology. Compressive strength tests were based on the previous research study, with curing intervals of 7, 14, and 28 days. The concrete quality test results indicate that concrete mixed with ceramic waste as a partial replacement for fine aggregates produces a strength that meets the standard for normal concrete, ranging between 30 - 40 MPa. A polynomial regression model synthesis based on the available laboratory data demonstrated good reliability, with an RMSE value of 0.172. Furthermore, using an Android emulator technology named BetonKU, the application successfully visualized the concrete mix design composition incorporating ceramic waste as a fine aggregate substitute according to the input data for the designed concrete strength.

Introduction

The rapid growth of industrialization and global urbanization has led to significant infrastructure development, contributing to environmental pollution due to the use of non-degradable materials (Haque, Mostafa, & Sah, 2021). This situation has created a shortage of construction materials, including raw materials for concrete, raising concerns about environmental pollution (Saikia & de Brito, 2014). Since coarse aggregates are the largest component in concrete mixtures, finding more sustainable alternatives to natural coarse aggregates is crucial (Basha, Ali, Al-Dulaijan, & Maslehuddin, 2020).

An increasing number of industries are using ceramic tiles in various types of construction. Globally, approximately 100 million tons of ceramic tiles are produced by different manufacturers (Zimbili, Salim, & Ndambuki, 2014). However, 20% to 30% of this production results in waste (Baraldi, 2016). Advances in concrete technology have had a positive impact on the environment by reducing the consumption of natural resources. Incorporating solid waste materials into traditional concrete production offers many benefits, such as recycling construction waste, reducing the environmental impact of cement production, and preserving natural resources (Yadav, Routiya, & Jethwani, 2017). Moreover, this waste contributes to improving the performance and properties of concrete. The use of ceramic waste powder as a partial replacement for Ordinary Portland Cement (OPC) in concrete mixtures provides multiple advantages, including reducing environmental hazards, saving energy, and lowering costs. The ceramic industry is a primary source of ceramic waste powder, which is generated during processes such as polishing and finishing (Singh & Srivastava, 2018).

Several studies indicate that ceramic waste powder can be used as a substitute for cement or fine aggregates in concrete. Ceramics offer numerous benefits, such as high resistance to weather conditions, insensitivity to sunlight, water, and dust, as well as chemical resistance, making them suitable for various applications (Zimbili et al., 2014). Ceramics are also known for their low friction coefficient, low density, corrosion resistance, affordability, and abundance. However, the properties of concrete, particularly compressive strength and durability, vary when ceramic waste powder is used as a cement substitute compared to fine aggregate replacement (Al-Ruqaishi, Allamki, & Poloju, 2019).

The ceramic waste used in the previous study was obtained from PT Keramik Diamond Industries, located in Bambe Village, Driyorejo District, Gresik Regency. The ceramics produced in this factory have product quality certifications (SNI ISO 13006:2010 - National Standard (SNI ISO 13006, 2010) and MS ISO 13006:2003 - Malaysian Standard (MS ISO 13006, 2014)) (BSN, 1989). Ceramic waste originates from the ceramic manufacturing process, where some pieces are defective or cracked during production (Jackiewicz-Rek, Załęgowski, Garbacz, & Bissonnette, 2015), ultimately becoming waste. Proper utilization of ceramic waste can transform it into a valuable resource and help mitigate environmental issues (BSN, 1989). Therefore, it is recommended to use ceramic waste as an additional fine aggregate in concrete mixtures, with percentage variations of 0%, 4%, 8%, and 12% of the fine aggregate (Ismawati & Andaryati, 2024a).

One of the rapidly developing technologies today is mobile applications, which can be utilized in daily life not only by the general public. The technology that supports mobile application development is known as an Android emulator (Guerra-Manzanares, Bahsi, & Nõmm, 2019). To use the most suitable Android emulator, a method is required that can produce optimal results from the emulator (Basuki & Aquariza, 2019).

We developed a framework and a prototype app that demonstrates how a predictive model for sustainable concrete mix design can be operationalized on a mobile platform, based on the characteristics of concrete according to the research of Ismawati and Andaryati (2024). While the current instance uses a specific dataset, the architecture is designed to accommodate updated models in the future. This research is a collaboration between civil engineering and informatics study programs.

While the compressive strength data for ceramic waste concrete and the principles of polynomial regression are established in literature, the originality of this work lies in the integrated synthesis and digital implementation of these elements. The specific contributions are:

1. A Practical Implementation Framework: We demonstrate a complete workflow from data synthesis and model validation to the development of a deployable mobile tool (BetonKU). This provides a template for digitizing other empirical material models.
2. Increasing Accessibility of Sustainable Practices: By embedding the optimized model in a free, mobile application, we lower the barrier for engineers and students to explore and specify ceramic waste in concrete mixes, directly supporting the adoption of sustainable construction methods.
3. Validation of the Concept: This study serves as a proof-of-concept that mobile technology can be effectively used to deliver specialized, data-driven mix

design guidance, a area less explored compared to web-based or desktop tools.

Methodology

In the previous research (Ismawati & Andaryati, 2024a), the mix design calculation is based on a Water-Cement Ratio (WCR) of 0.5 using the DOE (Department of Environment) method to determine the compressive strength and split tensile strength of both normal concrete and concrete mixed with ceramic waste at percentages of 4%, 8%, and 12%. This research follows ASTM (American Standard Testing and Material) standards for material testing, concrete compressive strength testing, and split tensile strength testing (Liu, Liu, Ma, Huang, & Li, 2015). From the results of the concrete compressive strength tests, the research team established a relationship between the percentage of ceramic waste and concrete quality. Using Android emulator technology, the BetonKU application was designed to determine the percentage of concrete mix materials.

Figure 1 illustrates the initial step in determining the composition of concrete mix materials, which is setting the Concrete Quality. In this step, the desired concrete quality is first established, as it influences the calculation of the required material composition. Next, the Calculation of Ceramic Waste Percentage is performed to determine the concrete material composition in more detail. The Calculation of Effective Fine Aggregate Percentage is then conducted according to the required concrete quality. Similarly, the Calculation of Effective Coarse Aggregate Percentage is carried out to determine the effective percentage of coarse aggregates (gravel or crushed stone) in the concrete mix. The Calculation of Coarse Aggregate Percentage ensures the correct proportion in the concrete mixture.

The result of all these calculations is the final material composition, which includes water, cement, coarse aggregate, and fine aggregate. This composition is used to achieve the desired concrete quality established in the initial step. Once the calculation process is completed, the diagram concludes at this stage after obtaining a mix composition that meets the required concrete quality. The final step involves the development of an Android emulator prototype, which will automatically calculate the percentage of substitute materials used in concrete production.

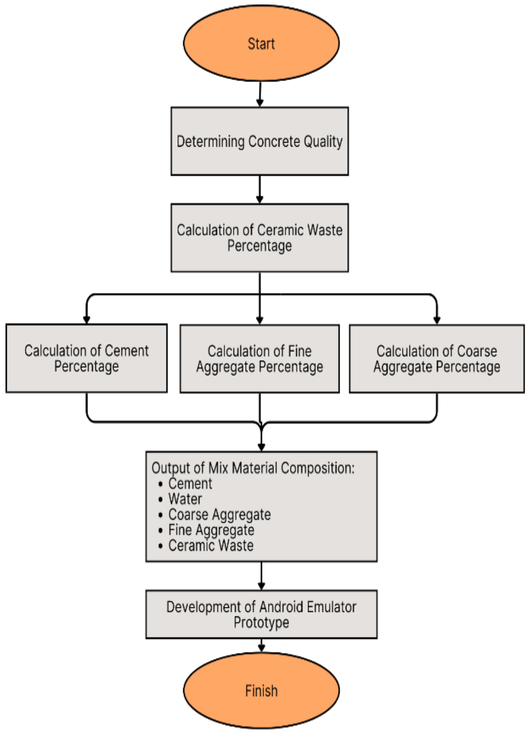


Figure 1. Research flowchart

Results and Discussion

The results and discussion carried out are concrete compressive strength test results, synthesis of correlation equation for the formulation of ceramic waste concrete mix design, and android emulator BetonKU. This result represents a proof-of-concept stage for future development work.

Concrete Compressive Strength Test Results

Ismawati and Andaryati (2024) conducted a study on the effect of using ceramic waste as a replacement for fine aggregate. The mix design formulation process used the DOE method, with a water-cement ratio of 0.4 (**Error! Reference source not found.**). The highest compressive strength of concrete containing ceramic waste as fine aggregate was achieved at a 12% ceramic waste replacement, reaching 39.32 MPa, which is approximately 26.31% higher than normal concrete (Table 2).The results of the compressive strength test for concrete mixed with ceramic waste as a fine aggregate replacement at 28 days of age are illustrated in the graph.

The X-axis represents the percentage of ceramic waste, while the Y-axis represents the compressive strength (MPa). Each data point is connected using the polynomial regression method (Hasanuddin & Kriswardhana, 2021), resulting in an upward-facing oval-shaped curve (Figure 2) with a coefficient of determination (R^2) of 0.977, indicating a strong correlation (Chicco, Warrens, & Jurman, 2021).

Figure 3 presents a graph showing the relationship between the total fine aggregate weight per m³ and the percentage of ceramic waste used, based on the mix design calculations (Table 1). Since the ceramic waste percentage is calculated relative to the fine aggregate weight in normal concrete, a

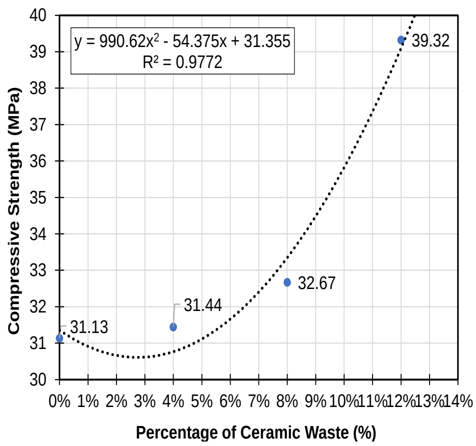


Figure 2. Concrete Quality vs. Ceramic Waste Percentage for Concrete Mix Design (fc 30 MPa)

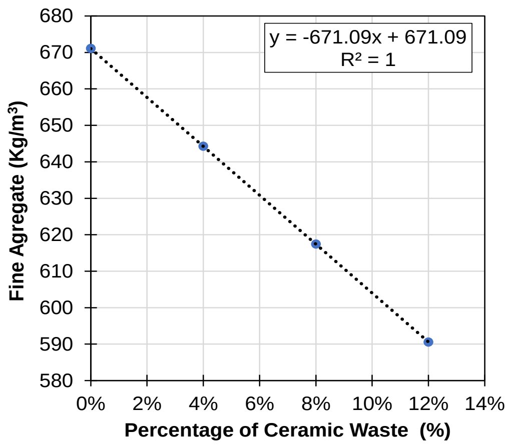


Figure 3. Fine Aggregate vs. Ceramic Waste Percentage for Concrete Mix Design (fc 30 MPa)

Table 1. Details of the formulation of the concrete mix design with ceramic waste (Ismawati & Andaryati, 2024)

Ceramic Waste Percentage	Cement (kg/m3)	Fine Aggregate (kg/m^3)	Ceramic Waste (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
0%	462.50	671.09	0.00	1080.09	188.68
4%	462.50	644.25	26.84	1080.09	188.68
8%	462.50	617.40	53.69	1080.09	188.68
12%	462.50	590.56	80.53	1080.09	188.68

Table 2. Compressive Strength Test Results of Concrete Mixed with Ceramic Waste (Ismawati & Andaryati, 2024)

Ceramic Waste Concrete Sample	Compressive Strength (MPa)		
	28 days	14 days	7 says
0%	31.13	22.47	20.43
4%	31.44	25.20	21.22
8%	32.67	28.60	22.64
12%	39.32	32.89	28.28

perfectly linear relationship is observed, as indicated by an R^2 value of 1.00.

Table 3. Calculation of RMSE Value for the Model

Designed Fc' (MPa)	% Ceramic Waste Lab. Data Correlation (y_i)	% Synthesized Ceramic Waste (y_i)	$\left(y_i - y_i\right)^2$
31	4.73	5.1813	0.20367
32	6.49	6.3818	0.01171
33	7.66	7.4815	0.03186
34	8.60	8.4804	0.01430
35	9.40	9.3785	0.00046
36	10.12	10.1760	0.00311
37	10.78	10.8720	0.00852
38	11.38	11.4680	0.00774
39	11.95	11.9630	0.00017
40	12.48	12.3570	0.01513
Number of Data (n)	10	TOTAL	0.29668
		$MSE = \frac{1}{n}\sum\left(y_i - y_i\right)^2$	0.02967
		$RMSE = \sqrt{MSE}$	0.17224

Synthesis of Correlation Equation for the Formulation of Ceramic Waste Concrete Mix Design

Based on Figure 2, a synthesis process was conducted to determine corresponding values between compressive strength and the percentage of ceramic waste, following the correlation line (Table 4). These synthesized values were then used to develop a correlation equation using the polynomial regression method (Figure 4). In this model, the target values (ceramic waste percentage) are placed on the Y-axis, w hile the predictor values (designed compressive strength in MPa) are placed on the X-axis.

Table 4. Synthesized Ceramic Waste Percentage Values for Designed Concrete Compressive Strength

No.	Designed Compressive Strength Value (MPa)	Ceramic Waste Percentage (%)
1.	31	5
2.	32	6.5
3.	33	7.7
4.	34	8.6
5.	35	9.4
6.	36	10.1
7.	37	10.8
8.	38	11.4
9.	39	12
10.	40	12.5

The synthesized correlation between the percentage of ceramic waste and the designed concrete compressive strength resulted in an R^2 value of 0.99, indicating a very strong relationship. The next step was to test the reliability of this synthesized correlation equation against the data graph in Figure 2.

To evaluate the accuracy of the model, the Root Mean Squared Error (RMSE) method

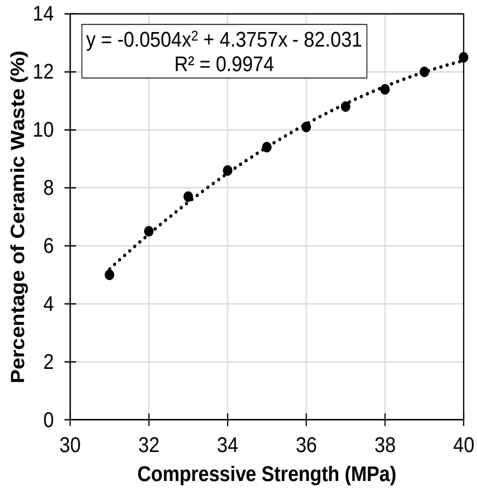
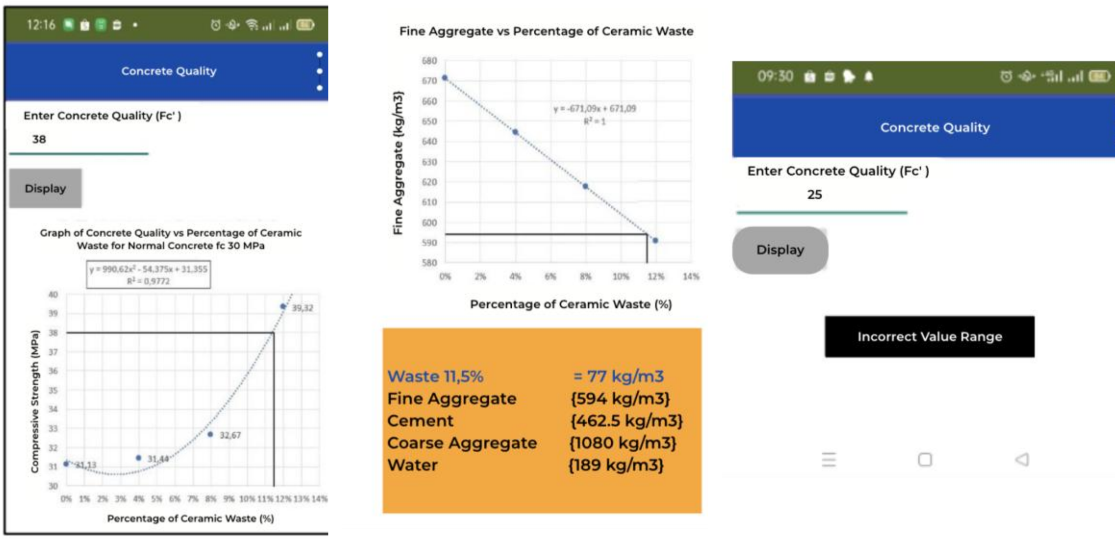


Figure 4. Synthesized Ceramic Waste Percentage Values for Designed Concrete Compressive Strength

was used. RMSE provides a quantitative measure of how well the model predicts values and helps in assessing and comparing the performance of regression models (Chicco et al., 2021). The RMSE calculation comparing the ceramic waste percentage from laboratory data with the predicted percentage from synthesized data resulted in an RMSE value of 0.172 (Table 4). This means that the potential prediction error for the ceramic waste percentage is 0.172%, indicating that the developed model has a high level of reliability.

(a) (b) (c)

Figure 5. (a) Initial Application Interface, (b) BetonKU Emulator Test Results, and (c) Detailed Information with Concrete Strength Value of 35 MPa



(a) (b) (c)

Figure 6. (a) BetonKU Emulator Test Results, (b) Detailed Information with Concrete Strength Value of 38 MPa, and (c) BetonKU Emulator Output When Input Value is Outside the 30-40 MPa Range

Android Emulator BetonKU

The previously described modeling results were implemented on an Android emulator platform to facilitate user accessibility. Figure 5a shows the application interface when the Android emulator is first launched. Users can register using an email or simply log in as a "Guest" if they prefer not to register with an email. The difference is that the concrete compressive strength test results cannot be displayed if the user logs in as a "Guest."

Figure 5a and Figure 5b show the test results of the BetonKU Emulator application with a concrete strength value of fc' = 35 MPa. The BetonKU Emulator application also provides detailed information on concrete mix requirements, including fine aggregate: 608 kg/m³, cement: 462.5 kg/m³, coarse aggregate: 1080 kg/m³, and water: 189 kg/m³.

As a second experiment, Figure 6a and Figure 6b presents the test results of the BetonKU Emulator application with a concrete strength value of fc' = 38 MPa. The application determined that the required ceramic waste percentage was 11.5%. Additionally, it provided detailed mix requirements, including fine aggregate: 594 kg/m³, cement: 462.5 kg/m³, coarse aggregate: 1080 kg/m³, and water: 189 kg/m³.

The BetonKU Emulator application is designed to restrict concrete strength values within the range of 30 – 40 MPa. If a user enters a value outside this range, the application displays an error message: "Invalid Range Value (Range Nilai Salah)", as shown in Figure 6c.

Concluding Remarks

Concrete with 12% ceramic waste as fine aggregate achieved the highest compressive strength of 39.32 MPa, representing an increase of approximately 26.31% compared to normal concrete. The use of ceramic waste as fine aggregate is feasible for enhancing compressive strength in concrete mixtures. The polynomial regression model synthesis based on available laboratory data demonstrated high reliability, with an RMSE value of 0.172. This study successfully developed and demonstrated an integrated workflow for implementing optimized ceramic waste concrete mixes. The primary contribution is not a new material experiment, but the translation of an existing empirical relationship into a functional Android application, BetonKU. This demonstrates a viable pathway to accelerate the adoption of sustainable materials by making research findings more accessible and actionable for practitioners. The framework presented can be adapted for other supplementary cementitious materials, highlighting its potential broader impact.

Future Work

To enhance the practical utility of the BetonKU application beyond its current proof-of-concept stage, future development will focus on incorporating flexibility. Potential upgrades include User-Defined Model Input which allowing users to input the coefficients of their own polynomial regression models (e.g., derived from their local materials and experiments), effectively making BetonKU a general-purpose concrete mix calculator for ceramic waste or other supplementary materials.

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