Research Article

Design of Structural Concrete with Bone China Fine Aggregate Using Statistical Approach

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In this rapidly industrializing world, recycling materials for construction is crucial for protecting natural resources and promoting sustainable human growth. It should be carefully considered because using the waste in the structural concrete is cost-effective but it is also constrained due to its declining qualities. Bone China waste (BCW) possesses pozzolanic properties and it was occasionally used in concrete by a few researchers. Therefore, in the current investigation, the workability, compressive, split tensile, and flexure strengths of the fresh and hardened characteristics are first determined. 0%, 20%, 40%, 60%, 80%, and 100 percent of (BCW) were utilized to replace natural fine aggregate (sand). The experiment’s findings demonstrate that every percentage of BCW replacement yields the desired characteristic strength, a mix with 60% BCW yielding the highest strength value. Furthermore, it was discovered that utilizing fine bone China instead of conventional fine aggregate in concrete increased the compressive, split tensile, and flexure strength. Through traditional laboratory experiments, a valid criterion for choosing an ideal mix combination of BCW as fine aggregate in concrete is quite laborious and time-consuming. As a result, the statistical models were presented based on the laboratory-tested compressive strength data for concrete including varying amounts of bone China waste as fine aggregate, which show resilience and normality when assessed using fundamental statistical techniques. Finally, a good agreement was found between the created models and the experimental results as well as with proven existing models. These models can forecast the compressive, flexural, and split tensile strengths of concrete when combined with bone China fine aggregates or any other type of fine waste. With this framework, one may examine the same factors as the study and make sure that concrete has the maximum strength and sustainability. An improved microstructure of the concrete was observed which exhibits fewer porosity and cracks when fine BCW was used in place of sand.

1. Introduction

The most commonly used building material is concrete, and it is the world’s second most frequently used material after water. Concrete combines fine and coarse aggregates bound with a fluid cement (i.e., cement paste). Aggregate is essential in concrete, contributing to 60–75% volume [1]. The huge volume of construction and demolished waste generated in concrete, bricks, and tiles put a lot of pressure on the city’s limited dumping sites [2]. However, due to limited natural resources for construction materials, recycled alternatives are required to satisfy the industry’s demands [3]. Using RCA in concrete is an innovative approach to a substitute for conventional natural aggregates from a sustainability perspective. The concrete industry utilizes many natural resources, resulting in significant economic, energy, and environmental losses. It consumes 50% of natural materials, uses 40% of energy, and generates 50% of all wastes [4].

Ceramics have also been widely utilized all over the world. However, a massive volume of ceramic waste is produced during the construction and destruction of structures [5]. This ceramic debris poses a major environmental risk and must be dumped in a huge landfill. Ceramic powder offers major health risks when it comes into contact with groundwater [6]. India’s bone China ceramics industry manufactures more than 343,000 tons of bone China...
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crockery annually. Burnt bone China crockery products account for around 15%–20% of total output in the same industrial sector and have minimal recycling options. These wastes are commonly dumped in landfills or open dumping grounds [7]. This ceramic waste presents a severe environmental risk but also requires ample landfill space for disposal. When groundwater comes into touch with ceramic powder, it can lead to significant health issues [8]. Bone China waste is a massive volume of the waste growing year after year in shops and manufacturers. Therefore, using waste in the concrete building industry is beneficial since concrete manufacturing costs less. The amount of waste bone China is gradually increased over the recent years due to an ever-growing use of bone China products. The landfilling of bone China waste is undesirable because it is not biodegradable, making it less environmentally friendly. Therefore, there is enormous potential for using bone China waste in the concrete construction sector [9].

The mechanical properties of concrete are improved by using BCCWP as a supplement to cement to a certain extent due to its pozzolanic behavior. By supplementing cement to a certain amount, BCCWP’s pozzolanic behavior enables it to improve the mechanical properties of concrete [10]. Siddique et al. discovered that BCCFA might be used as a fine aggregate in structural concrete (up to 40%) to provide significant strength and durability [8]. They use BCPW, bone China ceramic powder waste as a substitute for fine aggregate by volume. They found that the BCPW’s mechanical strengths have increased for up to a 100% volumetric replacement level. The more effective development of calcium silicate hydrate gel (CSH), which produces a dense microstructure, was responsible for the increased mechanical performance [9]. Sanitary ware fine aggregate replaced 20%, 50%, and 100% of the natural fine aggregate. They claimed that compared to reference concrete, mixes including ceramic aggregate showed increased capillary and immersion water absorption and greater chloride-ion migration. They concluded that more water absorption by the ceramic aggregate led to a greater ratio of water to cement, which caused the creation of pores in the concrete matrix [11]. Ceramic materials are highly durable, resistant to heat and fire, chemically inert, and strong [12]. According to Medina et al., adding up to 25% coarse sanitary-ware aggregate to concrete increased its compressive and split tensile strength. It was determined that the primary strength-gaining component was the pozzolanic behavior of the sanitary-ware aggregate [13].

Concrete’s slump and workability may be increased by adding the proper admixtures and using the pozzolanic characteristic of ceramic elements. The fresh density and hardened density of concrete containing Waste Ceramic (WC) reduce linearly as the increase of ceramic concentration. As the amount of ceramics added to concrete increases, the hardened qualities of concrete frequently decrease. However, compared to reference concrete (RC), ceramic concrete has a slightly greater compressive, elastic modulus, flexural, and split tensile. Compared to RC, ceramic concrete absorbs more water. WC materials have good abrasion, electrical, freeze-thaw resistance, and resistance to sulfate and sulfuric acid attack. As the percentage of ceramics in concrete increases, the depth of chloride-ion penetration decreases. As the amount of WC is increased, electrical resistance rises. As the percentage of ceramics in concrete rises, so do its durability qualities [14].

The thin section analysis provided information about adding calcium carbonate to the recycled aggregate and cement’s structure and helped to qualitatively determine the aggregate’s carbonation [15]. The geologists familiar with the procedure used in this method have shown it to be efficient, accurate, and time-efficient [16]. When waste is reused to make concrete products, production costs will decrease. Many administrations worldwide accepted the use of demolished waste in control measures for reuse as materials in concrete to minimize the use of virgin aggregates in terms environmentally, technically, and economically [17].

Wang et al. [18] suggested incorporating the pozzolanic materials, which accelerates the carbonation process with various mixing methods. Siddique et al. [8, 19, 20] studied on fine bone China ceramic aggregate (FBCCA) for pozzolanic properties for strength, durability, impact and aspects; and claimed that FBCCA provides extra CSH gel, which improves mechanical properties and can be used for structural applications. Very limited prediction models were reported especially with BCW as fine aggregate in concrete.

With this objective, the author’s done the present study in concrete with the replacement of BCW as fine aggregate to produce eco-friendly concrete, which can be used for low to medium-grade strength. Numbers of experiments were performed for varying replacements of sand with fine bone China waste to investigate the workability, compressive, flexural, and split tensile strength of differently mixed combinations. Microstructure’s concrete relationship with bone China fine aggregate is examined using thin section microscopy.

2. Experimental Program

2.1. Materials

2.1.1. Bone China Waste. Bone China is a form of porcelain made from kaolin, feldspathic material, and bone ash. Kaolin is a type of aluminum silicate that contains aluminum oxide and silicon dioxide and is used in concrete production. The mineralogical composition of BCW was analyzed by the X-ray Diffraction technique, as seen in Figure 1. The BCW property is given in Table 1.

2.2. Sample Selection and Preparation. Jaw crushers were used for crushing BCW materials to produce fine aggregate. Changing the distance between the crusher’s jaws meant a maximum aggregate size of 4.75 mm. The grading of the BCW, as fine aggregate, is done according to BIS 383 criteria (2016). BCW particle size distribution curves are presented in Figure 2.
2.3. Mixing Method and Mix Proportion. Table 2 shows the concrete mix proportions used in the present experiments. Materials were assembled according to the M20 grade mix design under the guidance of IS10262:2019 [21]. An optimized w/b ratio (i.e., water-to-binder) of 0.45 was used to make six different mixtures. BCW were used to substitute natural fine aggregate in proportions of 0%, 20%, 40%, 60%, 80%, and 100%.

3. Results and Discussion

Workability, compressive, flexural, and split tensile strength were tested for fresh and hardened properties on various design mixtures.

3.1. Workability. Concrete slump value determines a concrete mix’s consistency, flowability, compactibility, and pumpability. The effects of BCW on the workability of concrete were investigated. The result is shown in Figure 3 that when the percentage of BCW replacement increases, workability reduces due to higher water absorption of BCW.

An accurate prediction of workability is essential and practical for construction engineers. So, a regression-based analysis for predicting the workability of concrete for different percentages of BCW is performed. From Figure 4, well-fitted curves were developed using regression to generate the generalized equation with higher $R^2$ values for workability evaluation:

\[ Y_b = -0.3357x + 105.95; \quad R^2 = 0.9059, \]

where $Y_b$ is the Concrete workability for BCW, and $x$ is the percentage replacement of BCW.

3.2. Experimental Compressive Strength. The deciding factor for the applicability and sustainability of concrete is mainly governed by its compressive strength. The average compressive strength of concrete cubes specimens of size $150 \times 150 \times 150$ mm is tested with BCW for different design mixes for 7 and 28 days.

3.2.1. Effect of BCW on Compressive Strength of Concrete. The design mix proportions of 0, 20, 40, 60, 80, and 100% were evaluated to optimize BCW as a fine aggregate. The value of compressive strength of shown in Table 3. Increased compressive strength observed to 5.14, 9.08, 10.78, 2.25, and 0.98% for 7 days and 5.09, 7.7, 10, 1.45, and 0.45% for 28 days for replacement of 20, 40, 60, 80, and 100% as shown in Figure 5. Increased strength was observed up to 60% replacement due to the extra amount of CSH gel produced by fine BCW [Siddique et al.].

Furthermore, decreased compressive strength was observed beyond the 60% BCW ratio in the design mix, due to insufficient water content because the w/b ratio was fixed at 0.45 leading to poor hydration. However, excessive water also leads to a weak interface zone. As a result, the appropriate BCW content as fine aggregate was established at 60% based on the compressive strength aspect.

The compressive strength in this study is determined mainly by BCW replacement as fine aggregate. With traditional laboratory tests, a lot of time and effort is required to find an appropriate mix combination of BCW as fine aggregate in concrete for better performance. As a result, a mathematical relationship is developed between them for predicting the concrete compressive strength with various percentages of BCW (0, 20%, 40%, 60%, 80%, and 100%) to achieve the optimal value of BCW, which can be replaced with natural sand with a good coefficient of determination.

3.3. Statistical Analysis and Strength Prediction. The statistical method carried out to assess the impact of varying amounts of fine BCW on the compressive strength of concrete at various ages using experimental data is discussed. The steps
were performed sequentially to draw conclusions that could be used with any kind of fine waste in concrete.

3.3.1. Robustness. A robustness analysis will identify anomalous data, which are outcomes that do not match the other parameters. The absence of such data is critical to applying any statistical process since it affects the analyses’ significance.

Two methodologies were used to determine the presence of anomalous data (outliers):

Outliers are data not inside the diagram’s bounds, as specified by the whiskers, and may be visually identified within the box and whiskers plot. The robust indicators (median and trimmed mean 5%), unaffected by this sort of data, are compared to the traditional indicators (arithmetic

Table 2: Mix proportions.

| Mix | Cement (kg/m³) | Natural sand (kg/m³) | Bone China powder (kg/m³) | Coarse aggregate (kg/m³) |
|-----|----------------|----------------------|---------------------------|--------------------------|
| B0  | 485            | 727                  | 0                         | 1455                     |
| B20 | 485            | 582                  | 145                       | 1455                     |
| B40 | 485            | 436                  | 291                       | 1455                     |
| B60 | 485            | 291                  | 436                       | 1455                     |
| B80 | 485            | 145                  | 582                       | 1455                     |
| B100| 485            | 0                    | 727                       | 1455                     |

Table 3: Values for compressive strength (N/mm²) of mixes.

| Mix | 7 days        | 28 days       |
|-----|---------------|---------------|
| B0  | 12.50, 15.80, 14.30 | 19.00, 24.20, 22.80 |
| B20 | 13.20, 16.80, 14.90 | 20.40, 24.50, 24.46 |
| B40 | 13.90, 17.20, 15.37 | 22.50, 24.00, 24.60 |
| B60 | 14.80, 16.50, 15.89 | 23.70, 25.40, 23.50 |
| B80 | 13.80, 15.20, 14.59 | 21.20, 24.20, 21.56 |
| B100| 13.60, 15.40, 14.02 | 21.40, 22.80, 21.50 |

Figure 3: Workability of concrete when BCW are in the concrete.

Figure 4: Influence of BCW on the workability of concrete.
mean and standard deviation). Both types of indicators have relatively comparable values in the absence of errors.

Table 4 displays all the indications discussed for each mix at each age. The standard and robust indicators had extremely parallel values, and there were no outliers in the box and whiskers plots. As a result, all the data were integrated into the further study since they agreed with each other, and there were no anomalous data. Furthermore, the results demonstrate a high degree of homogeneity in all the mixes formed compressive strength behavior, which is critical when this trash is employed. As a result, the distribution of BCW was consistent throughout the board.

3.3.2. Normality. The histogram and quartiles of each variable were compared to those corresponding to a normal distribution, respectively, with three hypothesis tests: Anderson–Darling, Ryan–Joiner, and Kolmogorov–Smirnov, which analyses the symmetry of the data. The null hypothesis in all of these tests is that the data sample will have a normal distribution, which will be rejected if the p-value is less than the significance level (in this study, 0.05) as shown in Table 5.

The p-values of all three tests were greater than 0.05, indicating that the compressive strength of each combination at each age followed a normal distribution. However, there was one exception: at 28 days, mix B20’s histogram was incompatible with the normal distribution (Ryan–Joiner test) at a 95% confidence level, although being consistent with that distribution at a significance level of 0.01. This disparity was caused by the experimental data being concentrated in two small intervals with no intermediate values. A significance threshold of 0.01 was utilized for combination B20 at 28 days throughout the investigation.

3.3.3. Confidence Intervals. The arithmetic means confidence intervals, Table 6 shows us the range of values in which a variable may be found for a given degree of confidence. In this way, it is established, for instance, the overlapping can be possible between the strengths obtained in concretes with different percentages of fine BCW.

All of the mixes of the 7-day and 28-day confidence intervals overlapped in terms of the strong growth, demonstrating that a rise in the bone China fine waste produced a slower strength development. Comparing the confidence intervals of different BCW ratios, it is found that the strength of Mix, i.e., B60 has greater strength at both 7-day and 28-days age.
3.3.4. Compressive Strength Regression. From Figure 6, two well-fitted polynomial curves, one for seven days and the other for 28 days, were analyzed using regression to produce the following generalized compressive strength evaluation equation:

\[ F_c = -0.0005x^2 + 0.0515x + 14.197; \quad R^2 = 0.8139F_c \]

\[ = -0.0008x^2 + 0.0749x + 22.001; \quad R^2 = 0.8284, \]  

where \( F_c \) is the concrete compressive strength, \( x \) is the percentage replacement of BCW and \( R^2 \) is the Coefficient of determination. The regression model for the predicted compressive values with experimental compressive strength is shown in Figure 7.

3.4. Split Tensile Strength. To assess the tensile strength of concrete, a cylindrical specimen with a diameter of 150 mm and a height of 300 mm was tested for each design mix. Split tensile strength is crucial for establishing the viability of structures even though it is weaker than split compressive strength.

3.4.1. Effect of BCW on Split Tensile Strength of Concrete. Figure 8 shows the influence of BCW on the split tensile strength of M20 concrete. BCW is optimized by varying the proportions in concrete for 28 days of curing. In comparison to regular concrete, the strength of the concrete mix is increased when BCW is used in part replacement. The tensile strength increases 4.06, 3.72, 6.44, 1.69, and 1% with replacement of 20, 40, 60, 80, and 100% for 28 days. The results verified that the optimal BCW content as fine replacement was obtained at 60% based on the split tensile strength aspect.

3.4.2. Relationship between the BCW’s Compressive Strength and Splitting Tensile Strength. As shown in Figure 9, these experimental values of compressive strength (Fcs) and splitting tensile strength (Fspt) of BCW were subjected to

| Mix       | Anderson–Darling | Ryan–Joiner | Kolmogorov–Smirnov |
|-----------|------------------|-------------|--------------------|
| B0-7d     | 0.616            | >0.1        | >0.15              |
| B20-7d    | 0.625            | >0.1        | >0.15              |
| B40-7d    | 0.610            | >0.1        | >0.15              |
| B60-7d    | 0.518            | >0.1        | >0.15              |
| B80-7d    | 0.602            | >0.1        | >0.15              |
| B100-7d   | 0.304            | >0.1        | >0.15              |
| B0-28d    | 0.369            | >0.1        | >0.15              |
| B20-28d   | 0.061            | 0.021       | 0.083              |
| B40-28d   | 0.399            | >0.1        | >0.15              |
| B60-28d   | 0.128            | >0.1        | 0.149              |
| B80-28d   | 0.143            | >0.1        | >0.15              |
| B100-28d  | 0.100            | >0.1        | 0.119              |
| B100-28d  | 0.100            | >0.1        | 0.119              |

| Mix       | 95% confidence interval arithmetic mean (MPa) | 95% confidence interval for standard deviation using bonnet | 95% confidence interval for standard deviation using chi-square |
|-----------|---------------------------------------------|--------------------------------------------------------|--------------------------------------------------------|
| B0-7d     | (10.09, 18.30)                             | (0.24, 32.46)                                          | (0.86, 10.38)                                          |
| B20-7d    | (10.49, 19.44)                             | (0.26, 35.38)                                          | (0.94, 11.32)                                          |
| B40-7d    | (11.38, 19.59)                             | (0.24, 32.48)                                          | (0.86, 10.39)                                          |
| B60-7d    | (13.59, 17.86)                             | (0.12, 16.91)                                          | (0.44, 5.41)                                           |
| B80-7d    | (12.78, 16.27)                             | (0.10, 13.78)                                          | (0.36, 4.41)                                           |
| B100-7d   | (12.00, 16.67)                             | (0.13, 18.49)                                          | (0.49, 5.91)                                           |
| B0-28d    | (15.32, 28.68)                             | (0.86, 10.38)                                          | (1.40, 16.91)                                          |
| B20-28d   | (17.27, 28.97)                             | (0.35, 46.27)                                          | (1.23, 14.80)                                          |
| B40-28d   | (21.01, 26.38)                             | (0.16, 21.25)                                          | (0.56, 6.80)                                           |
| B60-28d   | (21.60, 26.79)                             | (0.15, 20.51)                                          | (0.54, 6.56)                                           |
| B80-28d   | (18.25, 26.38)                             | (0.24, 32.18)                                          | (0.85, 10.29)                                          |
| B100-28d  | (19.96, 23.84)                             | (0.11, 15.34)                                          | (0.40, 4.91)                                           |
regression analysis. The empirical relationship established using regression analysis is as follows:

\[ F_{c} = -0.0008x^2 + 0.0749x + 22.001 \]

\[ F_{c} = -0.0005x^2 + 0.0515x + 14.197 \]  
\[ R^2 = 0.8139 \]  
\[ F_{c} = -0.0005x^2 + 0.0515x + 14.197 \]  
\[ R^2 = 0.8284 \]  

This proposed relationship’s Coefficient of determination \((R^2)\) is 0.9061, representing a strong correlation. The proposed models were then compared to existing models using different well-established existing standard codes listed in Table 7 to evaluate the proposed model for determining split tensile strength from compressive strength. There is sufficient data to prove that all samples have a normal distribution from the Anderson-Darling test results, as shown in Table 8. Since their \(p\)-values are higher than 0.05.

\[ F_{c} = 0.781x + 3.3053 \]  
\[ R^2 = 0.8024 \]  

\[
\begin{align*}
\text{Mix Designation} & & \text{Split Tensile Strength (N/mm²)} \\
B0 & & 2.95 \\
B20 & & 3.07 \\
B40 & & 3.06 \\
B60 & & 3.14 \\
B80 & & 3.05 \\
B100 & & 3.10 \\
\end{align*}
\]  

**Figure 6:** Relationship between various design mix for BCW and compressive strength.

**Figure 7:** Relationship between experimental compressive strength and predicted compressive strength.

**Figure 8:** Average split tensile strength at different percentages of BCW at 28 days.
To check the reliability of the suggested models, a linear regression graph was stretched between the proposed model values and the estimated models, as shown in Figure 10.

3.5. Flexural Strength. In this study, flexural strength testing measures the concrete’s ability to survive bending stresses. The average flexural tensile strength was achieved by

$$Fspt = 0.5821(Fc)^{0.5275}$$

$$R^2 = 0.9061$$
comparing the M20 grade of concrete to all mixes developed using a 100 × 100 × 500 mm beam specimen. As a result, the flexural strength of various combinations of BCW cylinder specimens on the 28th day of curing was investigated in this study.

3.5.1. Effect of BCW on Flexural Strength of Concrete. The inclusion of BCW as a fine aggregate replacement also improves the flexural strength of concrete. Flexural strength increases 3.91, 6, 4.98, 0.35, and 1.06% with replacement of 20, 40, 60, 80, and 100% for 28 days as shown in Figure 11.

\[ F_s = 0.3337 \cdot (F_c)^{0.6879}, \]

where \( F_s \) is flexural strength in N/mm\(^2\), and \( F_c \) is compressive strength in N/mm\(^2\).

This proposed relationship’s Coefficient of determination \( (R^2) \) is 0.8893, indicating a strong correlation. Evaluated values from the proposed model from are compared to the

| Measured value | IS 456-2000 [27] \( F_s = 0.7\sqrt{F_c} \) | ACI-363, 2008 [23] \( F_s = 0.94\sqrt{F_c} \) | CSA 2010 [24] \( F_s = 0.6\sqrt{F_c} \) | NZS-3101,2017 [25] \( F_s = 0.8\sqrt{F_c} \) |
|----------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| 2.81           | 3.28                             | 4.22                             | 2.81                             | 3.75                             |
| 2.92           | 3.36                             | 4.32                             | 2.88                             | 3.84                             |
| 2.98           | 3.40                             | 4.38                             | 2.92                             | 3.89                             |
| 2.95           | 3.44                             | 4.40                             | 2.95                             | 3.93                             |
| 2.80           | 3.30                             | 4.25                             | 2.83                             | 3.78                             |
| 2.78           | 3.27                             | 4.21                             | 2.80                             | 3.74                             |

3.5.2. Relationship between the Flexure and the Compressive Strength for BCW. Figure 12 depicts the relationship in concrete between compressive and flexural strength with BCW. The empirical relationship obtained by regression analysis can be expressed as follows:

\[ F_s = 0.3337 \cdot (F_c)^{0.6879}, \]

Figure 11: Average flexural strength at different percentages of BCW at 28 days.

Figure 12: Relationship between the compressive and the flexural strength for different BCW percentage.

Table 9: Existing flexural strength estimate models use different standard codes.
Table 10: Variance and normality assumptions checked on different standard codes for the flexure strength test.

| Sample  | Variances | p-value | Decision                                      |
|---------|-----------|---------|-----------------------------------------------|
| Experimental | 0.0075   | 0.205  | Normal distribution observed in the table     |
| IS 456  | 0.0048   | 0.488  | Normal distribution observed in the table     |
| ACI-363 | 0.0067   | 0.374  | Normal distribution observed in the table     |
| CSA-2010| 0.0038   | 0.511  | Normal distribution observed in the table     |
| NZS-3101| 0.0061   | 0.531  | Normal distribution observed in the table     |

Figure 13: Relationship between experimental flexural strength and predicted flexural strength.

Figure 14: Microstructure of B60 sample. (a) Microstructure of B20 sample at 4X. (b) Ca(OH)₂ crystal Image at 40X. (c) C-A-S-H Image at 40X. (d) less porosity and cracks B60 sample at 4X.
well-established existing models (Table 9) for validation. Here is also sufficient data to prove that all samples have a normal distribution from the Anderson–Darling test results. Since higher p-values (i.e., > 0.05) are coming as seen in Table 10 and Figure 13 shows the relationship between the values by experiment and predicted values with $R^2$ as 0.889.

4. Microstructure Analysis

Determining the mechanism of concrete can be made easier due to recent advancements in petrographic techniques. Here, the microstructure analysis of concrete with fine BCW is done by using thin-section microscopy. The thin section of the petrography image of hardened concrete after 28 days is prepared for sample B60. Figure 14 shows the petrographic image of sample B60. These images demonstrate the microstructure development after hydration. Figure 14(a)) shows the major portion of concrete consists of C-S-H, calcium sulfoaluminate hydrates are also known as tobermorite gel, constitute around 70% of the volume of solids which is responsible for the higher strength. Calcium hydroxide crystal also called Portlandite, constitutes around 20% of the volume of solids and Calcium Sulfoaluminate Hydrates, C-A-S-H also called ettringite constitutes around 7% of the volume of solids in the hydrated concrete. Figure 14(b)) shows an image of Ca(OH)$_2$ crystal. Figure 14(c)) image of C-A-S-H, and as shown in Figure 14(d)) less porosity and cracks were observed with adding fine BCW.

5. Conclusions

This present work investigated the possibility of adopting BCW as fine aggregate instead of natural sand in concrete. The regression-based models were then developed using experimental compressive, flexural, and split tensile strength data at various percentages of BCW. The proposed models were compared to well-known existing strength prediction models to check their reliability. The following conclusions can be made in view of the findings.

(i) When BCW was used as fine aggregate, the improved compressive strength was observed by 10-11%. An increase of 9% and 10% was observed for 40 and 60% replacement of fine BCW to normal concrete. This is due to the pozzolanic behavior of BCW enhancing the strength properties and satisfying the characteristic strength of concrete.

(ii) The split tensile strength for all the mixes is between 2 and 4 N/mm$^2$. Hence all the replacement mixes satisfy the tensile strength requirement. An increase was observed by 3.75% and 6.44%, with the ratio of 40 and 60% replacement of fine BCW to normal concrete.

(iii) The flexural strength increase was observed by 6.00% and 4.98%, with the ratio of 40 and 60% replacement of fine BCW to normal concrete compared to normal concrete. The flexural strength for all the replacement mixes satisfies the I.S. requirement for the M20 grade.

(iv) As the amount of BCW increases in concrete, workability decreases. Hence, more water is needed to obtain the desired workability.

(v) A meaningful relationship between flexure and crushing strength (i.e., compressive) and split tensile and crushing strength containing bone China fine aggregates is developed. The accuracy of all models was examined which represents a good arrangement.

(vi) An enhanced microstructure of concrete was observed using BCW as fine aggregate in terms of porosity and cracks.

(vii) BCW can be used as fine aggregate in structural concrete for low-to medium-rise buildings (up to 60 percent). This substitute meets the engineering properties of M20 grade concrete mix design and can be used in moderate strength concrete [19].

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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