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RESEARCH PAPER

# A Novel Durability Based Concrete Mix Design Using Supplementary Cementitious Materials and Modified Aggregate Band Gradation

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**Abstract**
This study focuses on proposing a novel mix design method giving emphasis to the durability of concrete and replacing cement with supplementary cementitious materials (SCMs) at certain percentages. It also includes band gradation of aggregate that merges fine and coarse aggregates to result in a single well-packed combined gradation. Two replacement levels (20% and 35%) of fly ash and three replacement percentages (20%, 65% and 90%) of slag by weight of cement were used to prepare a significant number of concrete mixes. Compressive strength, workability and durability of the prepared mixes were determined. Rapid Chloride Permeability Test (RCPT) was carried out for measuring durability of concrete. From the prepared mixes, it was possible to achieve 90-day RCPT value as low as 216-coulomb and 28-day compressive strength up to 46.5 MPa. Several contour plots were developed correlating the three mix design parameters (compressive strength, slump and durability) with cement and water contents. Finally, using the plotted contours, a mix design process has been organized into five simple steps that can easily be followed in order to proportion an optimized ratio of cement, aggregate and SCMs for preparing durable and economical concrete mixes.

**Keywords** Concrete mix design · Fly ash · Slag · Durability · Combined aggregate gradation bands · Contour plots

## 1 Introduction

Mix design of concrete is done to proportion the amount of concrete constituents for making it robust, durable and economical. Therefore, the amount of cement required for

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any construction can be reduced through mix design process which would eventually help to curtail the construction cost as well as ensure construction sustainability. Fly ash and slag are two common industrial wastes that can be used as Supplementary Cementitious Materials (SCMs) to reduce carbon footprint [1, 2]. Both of these materials are byproducts that are recycled to be used in blended cement. Since they are waste products, the use of SCMs directly offsets the $CO_2$ emission that would otherwise be released in cement production. Also, it has been predicted that use of blended cement can reduce $CO_2$ emissions up to 20% by the year 2050 [3]. Fly ash, in fact, is the most pozzolanic material used in this world that reduces concrete permeability [4]. Hence, fly ash-based construction materials can be used as alternatives to Ordinary Portland Cement (OPC) because of their enhanced performance and sustainability [5].

Aggregate is another significant constituent of concrete which takes up to 60–90% of total concrete volume [6] and its gradation has a huge impact on characteristics of concrete [7]. In recent times, total aggregate gradation or combined aggregate gradation is gaining much popularity among civil engineers since combined gradation can better control workability, pumpability and shrinkage [8]. Furthermore, it combines the gradation of fine and coarse aggregate and forms a single gradation curve. This omits the calculations of determining two types of aggregate quantities separately. Holland [9] initiated the 8–18 band gradation which requires that the total percentage of fine and coarse aggregate retained on any one sieve be between 8% and 18%. Band gradations like 8–18 or 6–22 were recommended by researchers afterwards because these gradations reduce shrinkage [10]. However, there are some major drawbacks of 8–18 band gradation; for example, it includes a wide range of combined aggregate gradation where the ratio of fine aggregate to total aggregate (FA/TA) ranges from 0.28 to 0.65. The fineness modulus (FM) of combined aggregate also varies over a wide range of values under such band gradation. In addition, it was observed that these bands often do not make significant difference in concrete properties compared to the normally proportioned aggregates [11]. To overcome the drawbacks of 8–18 (or 6–22) gradation, two new modified band gradations for aggregates were developed by Ashraf and Noor [12]; these are 5-10-14-18 and 5-10-18-22. For aggregates belonging to these bands, the two most important parameters of grain size distribution, FM and FA/TA fall within a narrow range. The less variation in FM and FA/TA ensures that compressive strength and workability of resultant concrete vary insignificantly within these bands since aggregate properties dominate concrete properties. Concrete made with 5-10-14-18 and 5-10-18-22 bands were observed to perform better in terms of workability and compressive strength [6]. Durability performance of concrete made using these two aggregate bands was also found to be impressive by some researchers [13, 14]. Hence, these gradation bands of aggregate were used in this study for developing a new mix design approach focusing on concrete durability. Besides, use of fly ash and slag would reduce the construction cost as these materials are cheaper than cement. In addition, they would reduce carbon footprint as required amount of cement would be less [15].

Ensuring adequate durability is of utmost importance for concrete construction under aggressive environment. However, in general, the conventional concrete mix design procedures do not incorporate concrete durability as a mix design tool. A thorough literature review reveals that few previous studies are available that focused on mix design of sustainable and durable concrete. Wang [16] proposed a method for finding an optimal mix of fly ash and slag in ternary blended concrete which considered cost, strength, workability and carbonation. In this study [16], carbonation was used as a measure of durability. However, measurement of carbonation depth cannot be considered as an accurate measurement of permeability [17]. In addition, workability or slump value was not considered in measuring constituents of mixes. Tapali et al. [18] carried out a numerical iteration method for finding an optimum concrete mix which took into account durability in terms of carbonation and chloride ingress. Another study by Dan and Barai [19] addressed a sustainable concrete mix design incorporating fly ash and silica fume for reducing carbon footprint. In addition, various techniques and methods for obtaining sustainable concrete mix in terms of durability, $CO_2$ emission, cost, etc. were proposed in different studies by Lee et al. [20], Lee and Yoon [21], Kim et al. [22], and Sebaaly et al. [23]. However, no proper step by step mix design procedure was found that can be followed to find the optimum mix of concrete for target strength, slump and durability characteristics. ASTM C1202 [24] code can be used to quantify durability of concrete since it provides durability classifications of concrete in terms of chloride permeability. Therefore, a novel mix design procedure has been proposed in this research which follows ASTM C1202 [24] guideline for durability requirement and uses band gradation, fly ash and slag, for further improving durability of the concrete mix.

## 2 Material and Mix Proportions

The materials used in this research include OPC, fly ash, slag, locally available coarse aggregate and fine aggregate. Properties of these materials are discussed in this section.

**Table 1** XRF analysis of cement, fly ash and slag

| Compound | Cement composition (%) | Fly ash composition (%) | Slag composition (%) |
|---|---|---|---|
| Calcium oxide (CaO) | 62.5 | 1.99 | 40.10 |
| Silicon di-oxide ($SiO_2$) | 20.5 | 56.60 | 33.80 |
| Aluminium oxide ($Al_2O_3$) | 5.40 | 26.80 | 14.30 |
| Iron oxide ($Fe_2O_3$) | 4.60 | 5.27 | 1.50 |
| Magnesium oxide (MgO) | 1.89 | 0.853 | 4.81 |
| Sulphuric anhydride ($SO_3$) | 2.12 | 0.370 | 0 |

## 2.1 Cement

Ordinary Portland cement (OPC) similar to ASTM Type I [25] was used in this work. The unit weight of the cement was 3.15 kg/m$^3$. It had loss of ignition of 2.13%, fineness of 442 m$^2$/kg and soundness by Le Chatelier method [26] of 2.50 mm. The composition of the cement is shown in Table 1.

## 2.2 Supplementary Cementing Materials

Two types of SCMs, fly ash and slag were used in the study. The fly ash was classified as Class F fly ash since it had the total amount of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ contents equal to 88.67%, satisfying the requirement of ASTM C618 [27]. These two types of finely ground ash were added as a partial replacement of cement in various percentages in different concrete mixes. The oxide compositions of fly ash and slag are also presented in Table 1 along with OPC.

## 2.3 Aggregates

The two aggregate gradation bands (5-10-14-18 and 5-10-18-22) proposed by Ashraf and Noor [6] were used in this work. Locally available stone chips were used as coarse aggregate. Sylhet sand (FM 2.69) and local sand (FM 1.16) were mixed in the proportion of 1:1 as fine aggregate. The aggregates were separated into different sieves and then mixed according to the desired proportions of the two bands. Coarse and fine aggregates were combined to form these band gradations which simplified the aggregate content calculations in mix design process. Individual percent retained (IPR) curves are presented (Fig. 1) instead of the regular representation of gradation curves in order to better illustrate the aggregate bands.

In IPR curves, percent retained on each of the sieves are plotted against the corresponding sieve opening size. Both of the bands are presented in the same figure (Fig. 1) where the solid line represents 5-10-18-22 band gradation and the dashed bold line represents 5-10-14-18 band. For 5-10-14-18 band gradation, individual percent retained on #50 to #8 sieves should vary between 5% and 10% and individual percent retained on #4 to 12.5 mm sieve must vary between 14% and 18%. Similarly for 5-10-18-22 band, the percent retained requirement on sieves #50 to #8 is varied between 5% and 10% and on #4 to 12.5 mm sieve, the requirement is 18% to 22%. Thus, the 5-10-18-22 band clearly requires greater percentage of larger sized aggregates than 5-10-14-18. Any aggregate gradation chosen from these bands has properties varying within a very narrow range and

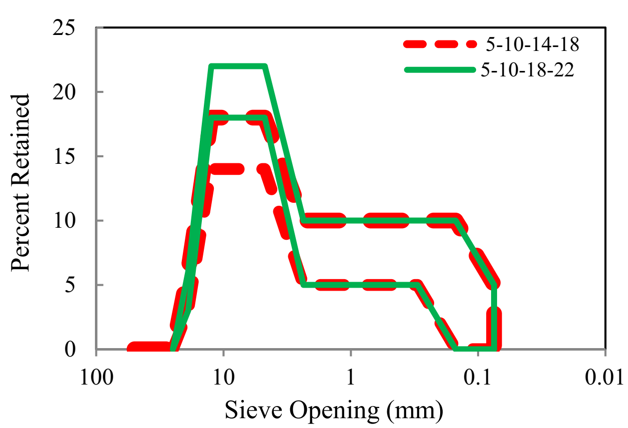


**Fig. 1** Individual percent retained (IPR) curve for bands 5-10-14-18 and 5-10-18-22

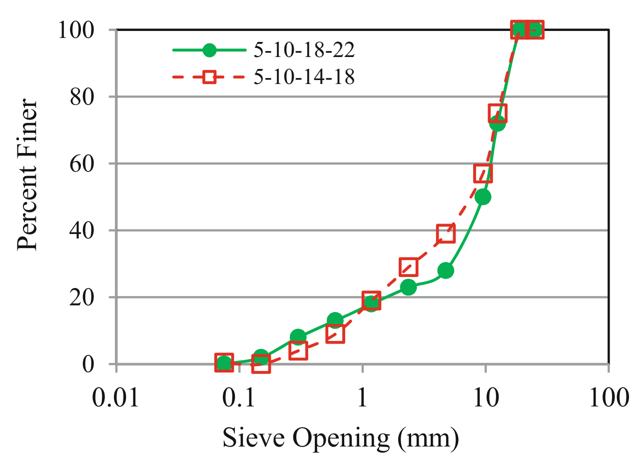


**Fig. 2** Gradation curves for 5-10-14-18 and 5-10-18-22 band gradations

Table 2 Properties of aggregates

| ID | Type | Absorption capacity, % | FM | Unit weight (kg/m$^3$) | Specific gravity (SSD) |
|---|---|---|---|---|---|
| Fine aggregate | | | | | |
| FA1 | Sylhet Sand | 1.69 | 2.69 | 1.765 | 2.7 |
| FA2 | Local Sand | 1.20 | 1.16 | 1.788 | 2.69 |
| FA | FA1:FA2 = 1:1 | 1.8 | 2.24 | 1.772 | 2.67 |
| Coarse aggregate | | | | | |
| CA1 | 12 mm downgrade | 0.8 | 6.06 | 1.616 | 2.68 |
| CA2 | 19 mm downgrade | 0.7 | 7.21 | 1.559 | 2.69 |
| Combined aggregate | | | | | |
| G1 | 5-10-14-18 | 0.7 | 5.32 | 1.865 | 2.64 |
| G2 | 5-10-18-22 | 0.7 | 5.92 | 1.831 | 2.65 |

eventually, produces concrete with less variation in fresh and hardened properties [12]. Therefore, any aggregate gradation selected from the aggregated bands can be considered as representative of the corresponding band. Consequently, one aggregate gradation was chosen from each of the aggregate gradation bands for producing concrete. The chosen representative combined gradation curves of the aggregate are shown in Fig. 2. The dry rodded unit weight values [28], FM values [29] and specific gravity [30] of aggregate gradations are presented in Table 2.

### 2.4 Mixture Proportions

Total one hundred and eight (108) mixes were prepared for collecting the required information for the proposed concrete mix design method. The mixes were designed for common ranges of concrete design strengths (low to moderately high strength concrete) usually used in the local construction industry. For proportioning of mixes, specific gravity of different constituents was used similar to ACI mix design. The workability of the mixes was measured (not controlled) in term of slump values to understand the effect of various proportions and types of SCMs. The durability of the mixes was evaluated through RCPT test. The obtained slump, compressive strength and RCPT values were then used to plot the contour diagrams.

Thirty-six (36) mixes were made using fly ash replacement levels of 20% and 35%. These two percentages were chosen because common fly ash replacement levels for Portland cement range from 15 to 35% [31]. BS EN 197-1 [32] allows the use of up to 35% fly ash as a cementitious component [33] for common composite cements. Slag, on the other hand, is more closely related to OPC than fly ash. This is one reason why slag can be used in much larger amounts as cement replacement [34]. The typical dosages of slag in blended cement vary from 6% to 95% according to BS EN 197-1 [32] and can be used in cement production according to ASTM specifications [35, 36]. Recent data [15, 37] indicates that slag replacement level up to 90% by weight of cement can be introduced in producing concrete and mortar samples. Hence, 54 mixes were prepared using slag replacement levels of 20%, 65% and 90%. The rest of the mixes were control mix containing 100% OPC. Each of these mixes was prepared using w/c ratios of 0.4, 0.5 and 0.6. Two aggregate gradations from each of the proposed bands were taken as discussed in Sect. 2.3. Same mixes were prepared for both of the aggregate gradations. The mix proportions along with the test results for concrete containing fly ash are shown in Table 3 and that for concrete containing slag are shown in Table S1 of supplementary section.

### 2.5 Test Methods

Slump test on fresh concrete and 28 day compressive strength tests were carried out according to ASTM specifications [38, 39]. Durability of concrete mixes was investigated by performing Rapid Chloride Permeability Test (RCPT) on concrete samples at 90 days of curing age as per the guidelines of ASTM C1202 [24] and recommendations from previous studies [40, 41].

## 3 Results and Discussion

### 3.1 Durability

The variations of RCPT values with fly ash and slag replacement are illustrated in Fig. 3a, b, respectively, for w/c ratio of 0.4. Other RCPT variation graphs (for w/c of 0.5 and 0.6) are presented in the supplementary section since they show similar trends. From the figures, it is evident that concrete with gradation band 5-10-14-18 show lower permeability than 5-10-18-22 band (up to 25% lower for fly ash and 31% lower for slag). Concrete having 35% fly ash, 5-10-14-18 band gradation, 350 kg/m$^3$ cement

**Table 3** Mix proportions and test results for concrete containing fly ash prepared using 5-10-14-18 and 5-10-18-22 band gradation

| Fly ash (%) | Cement content (kg/m$^3$) | Water content (kg/m$^3$) | Aggregate content (kg/m$^3$) | W/c | 5-10-14-18 band gradation | | | 5-10-18-22 band gradation | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Slump (cm) | 28-day compressive strength (MPa) | 90-day charge passed (coulomb) | Slump (cm) | 28- day compressive strength (MPa) | 90-day charge passed (coulomb) |
| 0 | 350 | 140 | 1862 | 0.4 | 7.6 | 32.3 | 3903 | 6.2 | 29.1 | 4128 |
| | 425 | 170 | 1785 | | 12.4 | 37.1 | 3888 | 11.2 | 33.2 | 3933 |
| | 500 | 200 | 1645 | | 15.3 | 39.7 | 3580 | 14.3 | 34.0 | 3609 |
| | 350 | 175 | 1862 | 0.5 | 15.6 | 28.5 | 4131 | 14.8 | 23.9 | 4190 |
| | 425 | 212.5 | 1785 | | 16.5 | 29.0 | 3994 | 16.3 | 25.4 | 4073 |
| | 500 | 250 | 1645 | | 21 | 31.6 | 3810 | 19.7 | 27.7 | 4061 |
| | 350 | 210 | 1862 | 0.6 | 16.5 | 19.2 | 4995 | 16.5 | 18.4 | 5090 |
| | 425 | 255 | 1785 | | 20.4 | 20.7 | 4806 | 20.3 | 18.9 | 4922 |
| | 500 | 300 | 1645 | | 23.6 | 22.1 | 4609 | 22.9 | 21.0 | 4889 |
| 20 | 350 | 140 | 1862 | 0.4 | 0 | 28.2 | 1917 | 0 | 26.3 | 2327 |
| | 425 | 170 | 1785 | | 1.8 | 34.1 | 1899 | 1 | 31.8 | 2300 |
| | 500 | 200 | 1645 | | 12.4 | 36.6 | 1678 | 10.8 | 32.4 | 2024 |
| | 350 | 175 | 1862 | 0.5 | 6.3 | 23.7 | 2754 | 5 | 21.9 | 2838 |
| | 425 | 212.5 | 1785 | | 15.3 | 26.0 | 2654 | 14 | 23.9 | 2701 |
| | 500 | 250 | 1645 | | 19.4 | 27.5 | 1742 | 18 | 25.8 | 2139 |
| | 350 | 210 | 1862 | 0.6 | 16.3 | 15.7 | 3398 | 16 | 14.1 | 3663 |
| | 425 | 255 | 1785 | | 20.2 | 16.2 | 3282 | 19.9 | 15.9 | 3373 |
| | 500 | 300 | 1645 | | 22.8 | 17.6 | 3123 | 22.3 | 17.1 | 3204 |
| 35 | 350 | 140 | 1862 | 0.4 | 0 | 26.1 | 1548 | 0 | 24.4 | 1857 |
| | 425 | 170 | 1785 | | 1.5 | 31.8 | 1476 | 0.5 | 28.1 | 1732 |
| | 500 | 200 | 1645 | | 10.3 | 33.7 | 648 | 9 | 29.2 | 864 |
| | 350 | 175 | 1862 | 0.5 | 4.3 | 21.7 | 2343 | 4 | 20.5 | 2498 |
| | 425 | 212.5 | 1785 | | 13 | 23.0 | 2291 | 12.2 | 21.9 | 2444 |
| | 500 | 250 | 1645 | | 17 | 25.3 | 1315 | 15.5 | 24.1 | 1452 |
| | 350 | 210 | 1862 | 0.6 | 14.9 | 14.4 | 2802 | 13.9 | 11.8 | 2843 |
| | 425 | 255 | 1785 | | 18.8 | 15.0 | 2635 | 18 | 14.7 | 2715 |
| | 500 | 300 | 1645 | | 20.9 | 15.9 | 2478 | 18.8 | 16.2 | 2556 |

content and w/c ratio of 0.4 reached RCPT value of 1890 C which lies in the low permeability range according to ASTM C1202 [24] (Table S2 of the supplementary section). The same concrete prepared using 5-10-18-22 band showed RCPT value of 2016 C which lies in the moderate permeability range. The difference between these two bands is that 5-10-14-18 band contained fewer amounts of particles (14% to 18%) on #4 to 12.5 mm sieve than that of 5-10-18-22 band (18% to 22%). Therefore, 5-10-14-18 band had greater proportion of finer particles resulting in denser concrete and hence, reduced permeability.

Durability has been found to increase gradually with increase of both fly ash and slag percentages. From Fig. 3a, it is observed that with 5-10-14-18 band, 350 kg/m$^3$ cement content and w/c ratio of 0.4, concrete reached high-, moderate- and low-permeability range as per ASTM C1202 [24] standard for 0%, 20% and 35% fly ash replacement, respectively. This implies that permeability of concrete decreased with increase in fly ash content as replacement of cement. Slag concrete with 5-10-14-18 band gradation, 350 kg/m$^3$ cement content and w/c ratio of 0.4 reached very low permeability range for both 65% and 90% replacement levels (Fig. 3b).

However, slag concrete with 20% replacement exhibited low-permeability characteristics and the RCPT values of control concrete was in high-permeability range. Addition of 90% slag reduced concrete permeability up to 95%, whereas 35% fly ash decreased it by 54%. The SCMs decrease the permeability of concrete by their micro filling property at early age and at later age, they reduce pore interconnectivity due to hydration of $Ca(OH)_2$ [42].

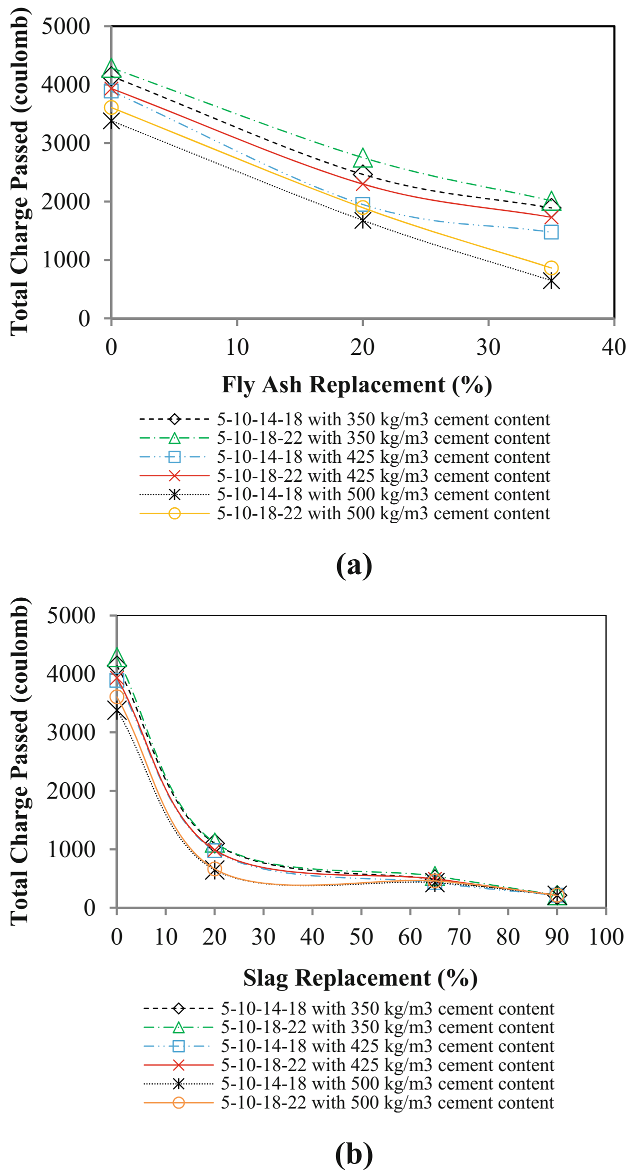


**Fig. 3** Variation of 90 day RCPT values for mixes with w/c ratio of 0.4 for **a** fly ash, **b** slag

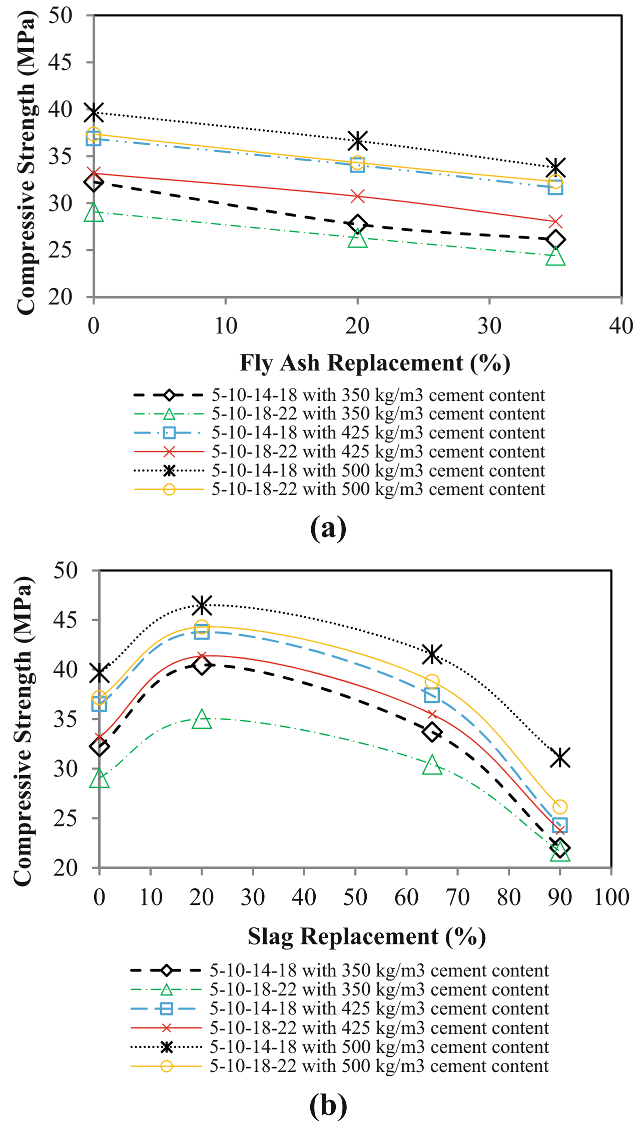


**Fig. 4** Variation of compressive strength for mixes with w/c of 0.4 for **a** fly ash, **b** slag

## 3.2 Compressive Strength

Variations of compressive strength with fly ash and slag replacement are presented in Fig. 4a, b, respectively, for w/c ratio of 0.4. Similar plots for w/c 0.5 and 0.6 are placed in supplementary section (Fig. S2). From Fig. 4a it is observed that 28-day compressive strength decreased with increased percentages of fly ash which agrees with the result obtained by Basha et al. [43]. It is also evident that concrete made with 5-10-14-18 band gradation exhibited greater 28-day compressive strength than 5-10-18-22 band concrete because the former resulted in denser concrete as it had larger fraction of fine particles.

It can be seen from Fig. 4b that initially, compressive strength increased with slag replacement and reached the highest strength at 20% replacement. After that, strength started to decrease. Ninety percent (90%) slag replacement resulted in the lowest strength. For cement content of 500 kg/m$^3$, w/c ratio of 0.5 and 5-10-14-18 band gradation, compressive strength of concrete made with 20% slag replacement was found to be 34.5 MPa which is 9% higher than the strength of control concrete. For 65% slag replacement, strength was almost equal to the strength of control concrete. Strength of concrete made with 90% slag replacement was 23.4 MPa which was 26% lower than the strength of control concrete.

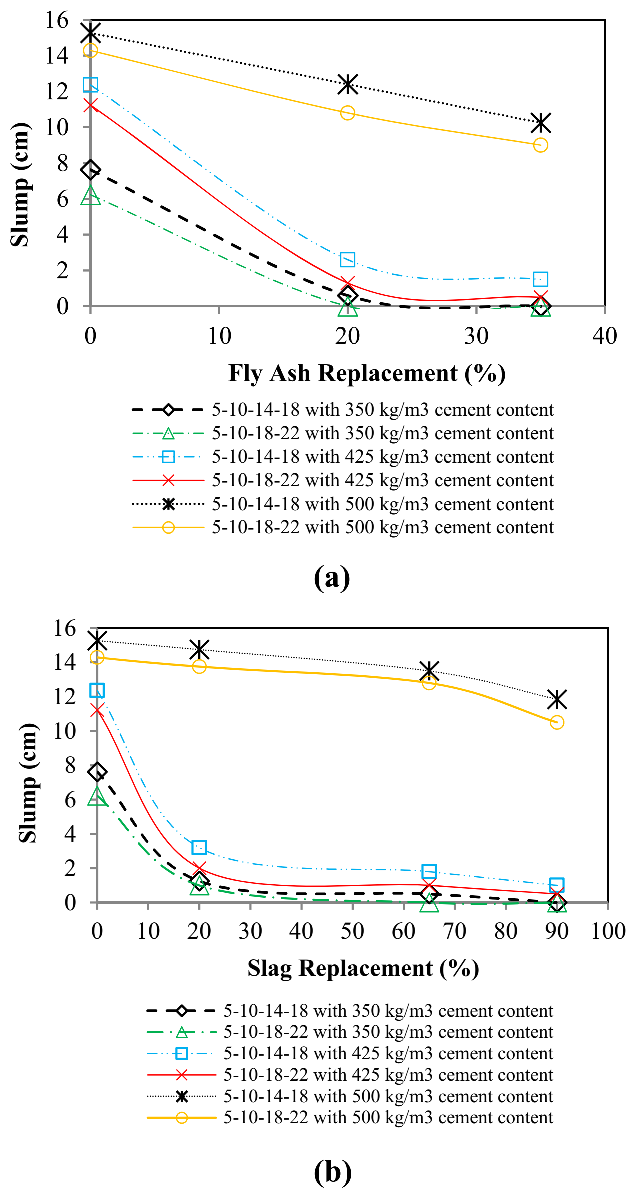


**Fig. 5** Variation of slump values for mixes with w/c of 0.4 for **a** fly ash, **b** slag

## 3.3 Workability

Slump variations for different percentages of fly ash and slag replacements are shown in Fig. 5a, b, respectively, for w/c of 0.4. The rest of the figures on slump variations are presented in supplementary section (Fig. S3). It is observed from these figures that slump value decreased with increase in both fly ash and slag replacement which agrees with the result obtained by Singh et al. [44] and Wardhono et al. [45]. This decreasing trend in slump can be attributed to the fact that these SCMs absorbed more water because of their hydraulic nature and high porosity. It was also found that slump was higher for aggregate gradation band 5-10-14-18 than 5-10-18-22 as the former band contains a greater percentage of smaller particles.

## 3.4 Development of Contour Plots

In this research, different contours were developed to show significant mix design parameters (compressive strength, slump, durability variation, water content and cement content) together instead of conventional plots. For fly ash, contour plots were developed for control concrete (0% SCM replacement), 20% and 35% replacement levels, and for slag, the similar plots were developed for 20%, 65% and 90% replacement levels. Other replacement levels can be expected to be interpolated from these plots.

The contour plots were used for the proposed mix design which has made the total mix design process easy and user-friendly. The development of contour plots showing the relationship among slump, compressive strength, water content and cement content for 20% fly ash replacement and 5-10-14-18 band graded aggregate is described below as an example. The detailed step by step procedures to develop a particular contour plot are presented in the supplementary section for better understanding of the readers.

i. Slump and compressive strength were plotted against water and cement contents as shown in Fig. 6a, b, respectively.
ii. The contours of slump and strength were then superimposed on each other to develop a single plot that combined four parameters (slump, compressive strength, water content and cement content) as shown in Fig. 6c. This plot eventually, became a part of the mix design steps. Since, Fig. 6 was formed by superimposing two figures, i.e., Fig. 6a, b, there are four parameters in this final plot. The ordinate and abscissa in the plot show cement content and water content in kg/m$^3$, respectively. The compressive strength values, ranging from 5 MPa to 40 MPa, are shown with the color bar bounded by dashed lines at 5 MPa intervals. The other lines (solid lines) intersecting compressive strength lines represent the slump values.

From Fig. 6c, cement content and water content can be calculated for a particular value of slump and compressive strength by drawing horizontal and vertical lines, respectively, and eventually, the required water-cement ratio can be determined. Similar contour plots were developed for other percentage replacements of fly ash and slag that are provided in Fig. S4 and Fig. S5 of the supplementary section.

Contour plots were also developed for different SCMs replacements and band gradations to establish the relationship among durability, water and cement content. The

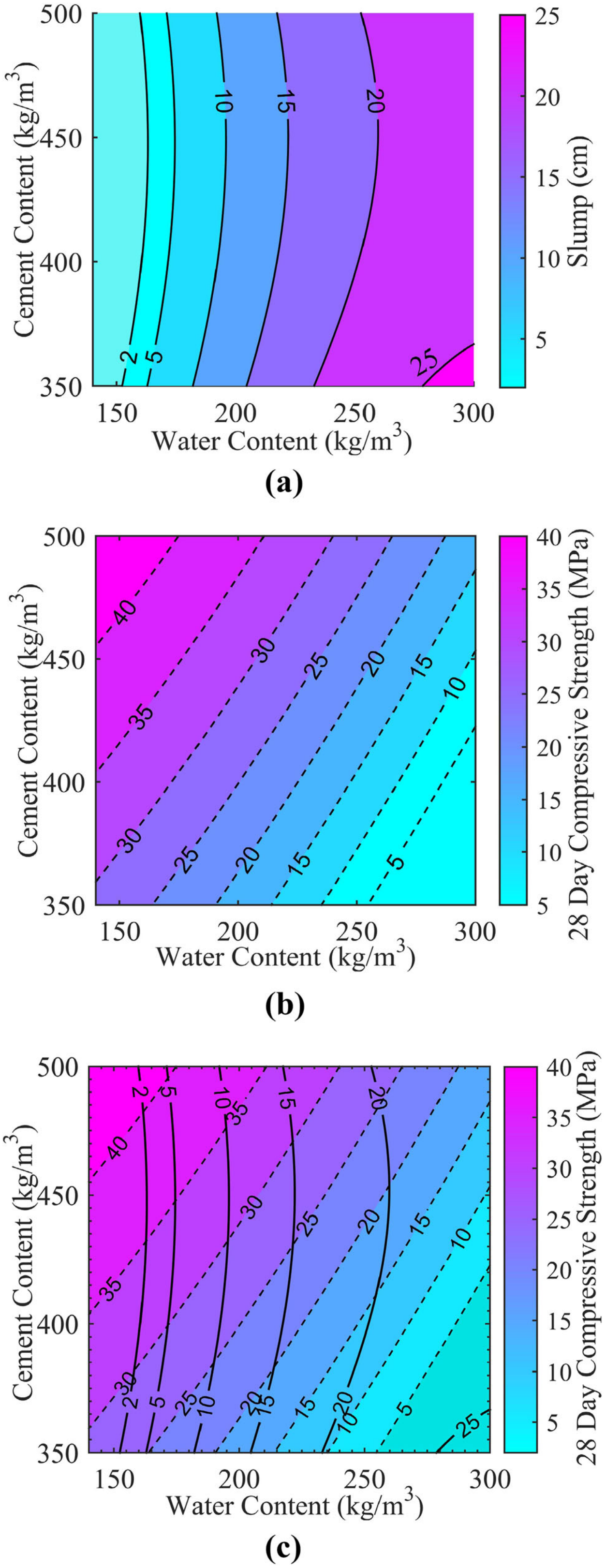


Fig. 6 Variation of **a** slump, **b** compressive strength **c** slump and compressive strength superimposed with water and cement contents for mixes of 5-10-14-18 band and 20% fly ash

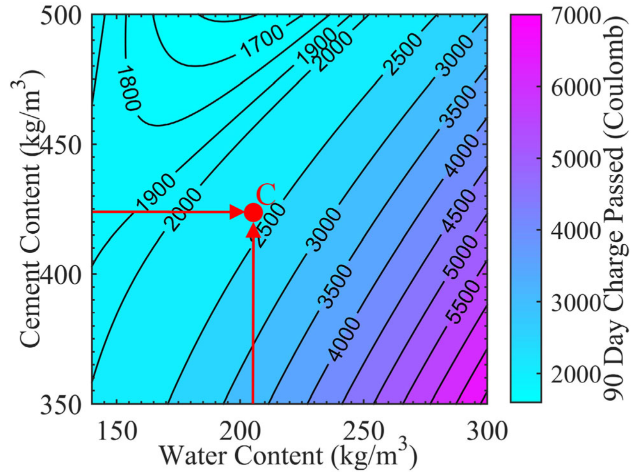


Fig. 7 Variation of charge passed (RCPT) with various water and cement contents for 20% fly ash replacement and 5-10-14-18 band gradation (the arrows are used in Sect. 6)

contour for 20% fly ash replacement and 5-10-14-18 band graded aggregate is shown in Fig. 7 as an example and the rest are provided in Fig. S6 and Fig. S7 of the supplementary section. Another type of contour was developed showing relationship among durability, slump and SCMs percentages. Two such plots are illustrated in Fig. 8 and all other contours are shown in Fig. S8 of the supplementary section.The properties of aggregate should be kept in mind while using these plots.

### 3.5 Proposed Mix Design Steps with Example

Stages of the mix design using fly ash as SCM are described through the following steps. Mix design using slag can be carried out in a similar manner which is described in the supplementary section of this paper.

**Example Problem**: A concrete mix has to be designed with target compressive strength of 27.5 MPa at 28 days and slump of 12 cm at the time of concrete mixing and has durability of moderate permeability range (2000 to 4000 C) according to ASTM C1202 [24]. Available Cement type is CEM I, SCM is fly ash and aggregate is locally available commercial stone aggregates.

**Step 1.** Calculation of fly ash percentage in concrete mix design: In this step, percentage of fly ash replacement is chosen from slump and durability requirement graphs (Fig. S8). If 5-10-14-18 band gradation is used, then from Fig. 8a, 20% fly ash replacement for 12 cm slump and moderate durability (2000–4000 C permeability) can be used. Twenty percent (20%) fly ash replacement can be chosen for 5-10-18-22 band as well which is illustrated in Fig. 8b.

**Step 2.** Determination of Water Content, Cement Content and Gradation Band from Workability and Strength

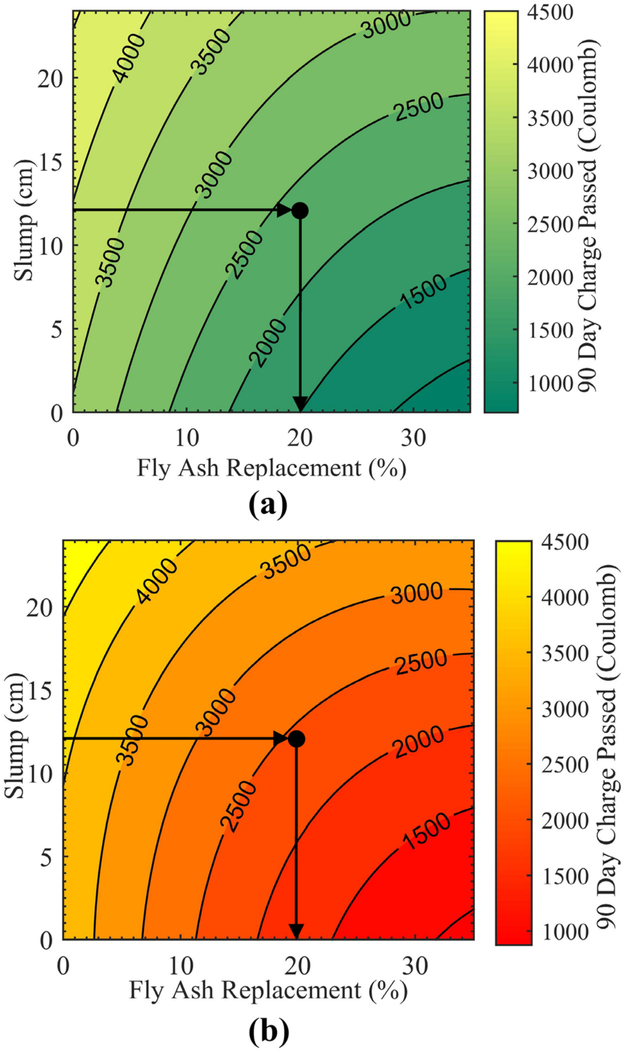


**Fig. 8** Variation of permeability classes with slump and fly ash replacement percentages for aggregate band **a** 5-10-14-18 and **b** 5-10-18-22 (Example problem)

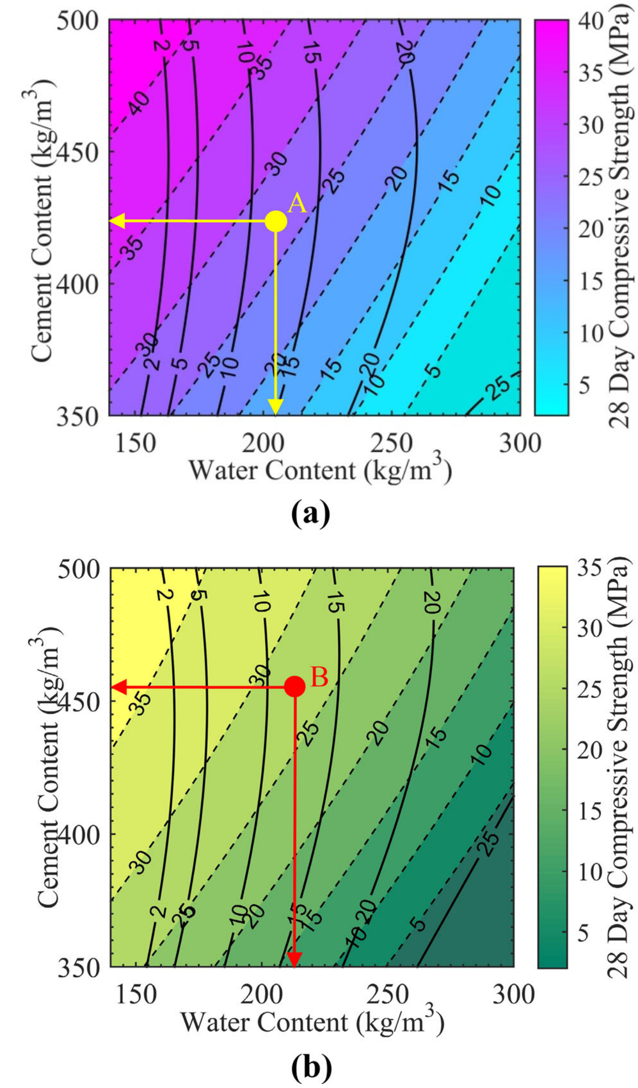


**Fig. 9** 28-day compressive strength and slump variations for cement with 20% fly ash replacement and **a** 5-10-14-18 band gradation and **b** 5-10-18-22 band gradation

Requirements: With the values of required concrete compressive strength and workability, water and cement content can be determined from Fig. S4 (showing compressive strength and slump variation with water and cement contents) of supplementary section. Since fly ash replacement level is determined to be 20%, Fig. S4 (b) and Fig. S4 (e) need to be used which are presented in Fig. 9a, b, respectively. For required 28-day compressive strength of 27.5 MPa and slump of 12 cm, let the points A and B be selected on Fig. 9a, b, respectively. It is apparent that band gradation 5-10-14-18 gives water content of 205 kg/m$^3$ and cement content of 424 kg/m$^3$. On the other hand, band gradation 5-10-18-22 gives water content of 213 kg/m$^3$ and cement content of 455 kg/m$^3$. Though the water-cement ratio for aggregate gradation band 5-10-18-22 is slightly less than that for 5-10-14-18, cement content required for the latter one is much higher. Hence, gradation band 5-10-14-18 is chosen and water-cement ratio is calculated to be 0.483.

**Step 3.** Modification of Water Content considering Durability Parameter: Using the cement content chosen in step 2, the modified water content is determined from contour plots of durability versus cement and water. First it is checked whether the selected water and cement contents produce the required concrete durability or not. If the chosen water and cement contents result in an RCPT value higher than required range, water content needs to be lowered and vice versa. The cement content and water content chosen from step 2 (424 kg/m$^3$ and 205 kg/m$^3$, respectively) result in point C on Fig. 7 that corresponds to 2400 C which lies in moderate permeability range. So no modification in cement and water content is required.

**Step 4.** Calculation of Cement Content: After knowing the water content and water–cement ratio, required cement content can be calculated by dividing the former value with the latter. As no modification of cement and water content was required in step 3, cement content is chosen to be 424 kg/m$^3$ as selected before.

**Step 5.** Calculation of Total Aggregate Content: Total aggregate content is determined by absolute volume method using the water and cement contents. In the first step, the portion fulfilled by cement and water is determined for unit volume of concrete. Then, the rest of the volume is measured which has to be occupied by the aggregates. For unit volume of concrete, (1 m$^3$),

- Cement volume = Cement content (kg)/(sp. gravity of cement × unit weight of water (kg/m$^3$)) = 424/(3.15*1000) = 0.135 m$^3$
- Water volume = Water Content (kg)/unit weight of water (kg/m$^3$) = 205/1000 = 0.205 m$^3$
- Aggregate volume = 1-cement volume (m$^3$) -water volume (m$^3$) = 1-0.135-0.205 = 0.66 m$^3$

## 4 Validation of the Proposed Mix Design Using Laboratory Experiments

Four concrete mixes were prepared in the laboratory to validate the proposed concrete mix design method. Two mixes were prepared using fly ash as SCM and using 5-10-14-18 and 5-10-18-22 band gradations, respectively. Rest of the two mixes were prepared using slag as SCM and using 5-10-14-18 and 5-10-18-22 band gradations, respectively. The target and resulted 28-day compressive strength, durability class and slump values along with the mix design parameters for a mix prepared with fly ash are shown in Table 4 and that of the other three mixes are presented in Table S3 of the supplementary section. It was found that the achieved compressive strength was higher than the corresponding target strength. Slump value was found to be within the target slump range. The passed charge value from RCPT test was found as 1430 C which also fell in the low permeability range according to ASTM C1202 [24] as per design requirement.

## 5 Conclusions

In this research, a comprehensive mix design process has been developed after analyzing the results of different mixes. In addition to compressive strength and workability, durability has been used as a mix design parameter. Mixes were prepared using two types of combined aggregate bands (5-10-14-18 and 5-10-18-22) instead of conventional aggregate gradations because concrete made with these bands perform better than code specified aggregate gradations. Contour diagrams have been used in the mix design steps for easier interpretation. Fly ash and slag were used in the mixes to further improve the durability of concrete. Finally, the proposed mix design method has been validated by preparing four different mixes and comparing their test results with target design values. The following conclusions can be drawn based on the outcome of the research work:

i. Compressive strength of concrete gradually decreased with increased percentage of fly ash. In case of slag, 20% replacement resulted in the highest compressive strength for all the mixes and then it was decreased with further increase of slag percentage. Durability, on the other hand, was observed to perform better with the increase of both of the SCMs. Fly ash replacement resulted in a gradual improvement of concrete durability. For slag, however, a sharp drop in permeability value was observed for 20% replacement compared to control concrete. Then there was insignificant decrease in coulomb values for further addition of slag.
ii. Contour plots were developed to establish correlations between different significant mix design parameters, i.e. strength, slump, durability, SCM percentage etc. Four parameters have been represented simultaneously in one plot which makes the mix design steps convenient.

**Table 4** Test results for trial mix L-1

| | SCM type | SCM (%) | Aggregate Band | Cement Content (kg/m$^3$) | Water Content (kg/m$^3$) | w/c Ratio |
|---|---|---|---|---|---|---|
| Mix details | Fly ash | 35 | 5-10-14-18 | 470 | 191 | 0.41 |
| | 28-Day Strength (MPa) | Slump (cm) | Charge Passed (coulomb) | Permeability Class | | |
| Target | 34.5 | 4–6 | – | Low | | |
| Achieved | 34.7 | 5 | 1430 | Low | | |

iii. Fly ash and slag were used in the proposed mix design process and it was observed that these two supplementary materials improve concrete durability due to their pozzolanic properties. A designer can use this mix design approach to improve durability of the mix as well as to reduce the cost and environmental impacts of cement production.
iv. The proposed concrete mix design used combined aggregate band gradations i.e., 5-10-14-18 and 5-10-18-22 that can achieve high durability and compressive strength (90 day RCPT value as low as 216 C and 28 day compressive strength up to 46.5 MPa.)
v. 5-10-14-18 band resulted in slightly better durability and higher compressive strength than 5-10-18-22 band. This was due to the fact that 5-10-14-18 aggregate band had higher percentage of finer particles that ensured denser packing.

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