Properties of alkali-activated concrete (AAC) incorporating demolished building waste (DBW) as aggregates

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Abstract: This study was undertaken to evaluate the potential of demolished building waste (DBW) as aggregates in alkali-activated concrete (AAC). A recent road-widening activity led to the demolition of commercial buildings along National Highway 275, Bangalore-Bantwal, India. DBW was collected from these sites and processed manually at the laboratory facility of CHRIST (Deemed to be University). Processing of DBW was done to obtain both waste coarse and fine aggregates from demolished concrete and brick waste units, respectively. AAC was synthesized by fly ash, ground granulated blast furnace slag, sodium hydroxide, sodium silicate, along with waste aggregate replacement rates of 0, 25, 50, and 75% by weight of natural aggregates. Fresh and hardened properties of developed concrete mixtures were experimentally determined. Results of the study indicate that 28-day compressive strength of 30.4 and 21 MPa was obtained for AAC with 25 and 50% DBW aggregates, which was 8.6 and 36.9% lower than control mix, respectively. Further, there was an increase in the water absorption and a reduction to acid resistance for all the AAC mixes with DBW aggregates. Based on the results obtained, it was observed that AAC with 25 and 50% DBW aggregates find great potential in civil engineering applications.

Subjects: Concrete & Cement; Waste & Recycling; Construction Materials

Keywords: Alkali-activated; concrete; demolished building waste; strength; durability

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PUBLIC INTEREST STATEMENT
Demolition waste is primarily generated due to destruction of buildings, roads, bridges, etc. In India, urbanization and road widening activities lead to the generation of demolition waste in huge quantity. Further, there is limited use of demolition waste in the construction industry, and still large portion of this waste is dumped, either in demolition debris landfill or municipal solid waste landfills. Therefore, effective use of demolition waste in construction industry is a topic of importance and has been considered in this research article.
1. Introduction
Demolished building waste (DBW) is on rise due to constant urbanization and developments in infrastructure projects in India. Most of the commercial buildings are constructed in close proximity to roadways with minimum offset from pavement shoulders, which leads to demolition due to road widening projects. DBW generated in urban regions is substantial and often landfilled incurring loss to the construction industry. Also, field observations show that in many instances it is discarded inappropriately which can cause harm to people and the environment. Therefore, it is imperative to effectively utilize DBW in construction industry. Numerous efforts have been made to study DBW in construction industry (Coelho & de Brito, 2012; Leite et al., 2011; Lin et al., 2010; Panizza et al., 2018; Perez et al., 2012; Poon & Chan, 2006a, 2006b, Poon et al., 2002, 2009; Prestes et al., 2012; Rodrigues et al., 2013; Sales & de Souza, 2009; Silva et al., 2014). Lin et al. (Lin et al., 2010) demonstrated the effectiveness of waste brick as pozzolanic material, which can partially replace Portland cement. In another study, the use of recycled aggregates from construction and demolition (C&D) waste in hot mix asphalt was evaluated. The results of the study indicate that recycled aggregates in hot mix asphalt possess poor stripping behavior, and increased absorptive nature of the porous cement mortar demands greater binder content (Perez et al., 2012). Recycled aggregates from C&D waste has also been used in production of cement concrete. Poon et al. (Poon et al., 2002) showed the effective usage of recycled aggregates in concrete products. Bricks and blocks manufactured with 25% to 50% replacement of natural aggregates with recycled aggregates have shown satisfactory results. Also, an increased usage of recycled aggregates was recommended in footpath applications, where the required strength is slightly lower. Use of recycled concrete aggregates and crushed clay brick in paving blocks have also been attempted (Poon & Chan, 2006a). Results indicate that crushed clay bricks reduce the density and strength of concrete and increase the water absorption substantially. Accordingly, 50% recycled concrete aggregate and 50% crushed clay bricks satisfy the minimum strength requirement for the use of concrete in pedestrian facility.

In recent times, another subject that has drawn attention among the researchers, is the use of recycled aggregates in alkali-activated and geopolymer concrete to replace natural aggregates (Hu et al., 2019; Kathirvel & Mohan, 2017; Nuaklong et al., 2016; Shaikh, 2016; Shi et al., 2012; Tang et al., 2019, 2020). The results of the study conducted by Nuaklong et al. (Nuaklong et al., 2016) indicate that recycled concrete aggregate can be effectively used in geopolymer concrete. Even though the strength properties of concrete were affected negatively, it possessed enough compressive strength (i.e., 30.6 to 38.4 MPa) to be considered for civil engineering applications. The properties of geopolymer concrete incorporating recycled aggregates were compared with that of Portland cement concrete by Shi et al. (Shi et al., 2012), and the results obtained indicate superior mechanical properties of geopolymer concrete having denser paste structure with the absence of calcium hydroxide. There are limited studies pertaining to the use of concrete and brick waste as replacement to natural aggregates in alkali-activated concrete. Particularly, its potential to replace both the coarse and fine fraction of the natural aggregates. Therefore, this study aims at developing alkali-activated concrete with the use of concrete and brick waste from locally demolished commercial buildings, as a replacement to natural coarse and fine aggregates, respectively.

2. Materials and methods
2.1. Materials
DBW was acquired from a site situated on National Highway 275, Bangalore-Bantwal, India. Most of the demolished buildings were 15 to 20 years old and consisted of brick masonry walls with reinforced concrete frames. According to a field survey conducted, an approximate estimate of DBW for an area of 1000 m² was 2000 tons, which consisted of 975 tons of cement concrete, 850 tons of brick masonry, and 175 tons of cement mortar, excluding other wastes like rubber, plastic, ceramic, etc. The strength test conducted on locally available materials such as bricks and Portland cement concrete revealed that most bricks had compressive strength ranging between 5 and 7.5 MPa, and the concrete compressive strength ranged between 25 and 30
MPa. DBW was collected from the site and processed manually at the laboratory. Processing involved separation of demolished cement concrete and brick masonry units. Further, breaking in to smaller fractions were done manually. Figure 1 shows the DBW before and after processing. Natural aggregates were acquired from local quarries, which are mainly granite. Precursor materials used for preparation of alkali-activated concrete was fly ash (FLA) and ground granulated blast furnace slag (GGBS). Table 1 presents the physical and chemical properties of precursor materials which comply with previous published study (Hossiney et al., 2020a, Hossiney et al., 2020b). Alkaline solution was prepared by mixing NaOH solution and Na$_2$SiO$_3$ solution. Analytical grade NaOH pellets with 98% purity was used. While, Na$_2$SiO$_3$ solution consisted of Na$_2$O = 14.7%, SiO$_2$ = 29.4%, H$_2$O = 55.9%. For preparation of NaOH solution normal tap water was used.

2.2. Mixture proportioning
Mixtures were proportioned to evaluate the feasibility of DBW (consisting of concrete and brick waste) as a replacement for natural aggregates in AAC, and not to optimize the mix design. Therefore, all the important parameters required for synthesizing AAC was kept constant, and only the amount of DBW varied. The important parameters were selected based on findings of previous study ( Deb et al., 2014; Hardjito & Rangan, 2005; Nath & Sarker, 2014). The details of concrete mixtures evaluated are presented in Table 2. AACWA0 indicates alkali-activated concrete with no DBW. AACWA25 indicates 25% replacement (by mass) of natural coarse aggregates (NCA) by concrete waste aggregate (CWA), and 25% replacement (by mass) of natural fine aggregates (NFA) by brick waste aggregate (BWA). Similarly, AACWA50 and AACWA75 mixes were proportioned.

2.3. Specimen preparation
Specimens were made in steel molds. For each of the different tests a replica of three specimens were prepared. NaOH solution was prepared 24 hours prior to the production mix by dissolving the required quantity of NaOH pellets in water. To prepare 8 M NaOH solution, 320 g of NaOH pellets were dissolved in 1000 ml of water. Alkaline solution was prepared by mixing determined quantities of NaOH solution and Na$_2$SiO$_3$ solution, 1 h before the production mix. Concrete mixtures were prepared in a pan mixer. Prior to mixing, all the aggregates were kept in moist condition for 24 hours. This was done to avoid absorption of alkaline solution by dry aggregates during mixing. Prewetted aggregates

| Material | Specific gravity | Finer than 45 μm (%) | Specific surface area (m$^2$/kg) | SiO$_2$ (%) | Al$_2$O$_3$ (%) | Fe$_2$O$_3$ (%) | CaO (%) |
|----------|-----------------|----------------------|----------------------------------|-------------|----------------|---------------|---------|
| FLA      | 2.62            | 70.5                 | 699                              | 46.5        | 19.54          | 13.46         | 7.61    |
| GGBS     | 2.78            | 88                   | 718                              | 35.8        | 17.7           | 0.61          | 36.4    |
were drained off with excess surface moisture and added to pan mixer. NCA, NFA, CWA, BWA, FLA and GGBS were dry mixed thoroughly in pan mixer for 3 minutes. After dry mixing, alkaline solution was added into pan mixer. Mixing continued till homogenous mix was obtained. Fresh mix was immediately used to determine the slump and unit weight of concrete. Steel molds were filled in layers and compacted by tamping rod. Further, table vibrator was used for approximate 30 s to compact the specimens. Figure 2 shows the mixing process and specimens prepared.

### 2.4. Test methods

Aggregates were tested for their physical and mechanical properties. These tests included particle size distribution in accordance with IS: 2386 Part I (IS: 2386 Part I, 1963), density, specific gravity, water absorption in accordance with IS: 2386 Part III (IS: 2386 Part III, 1963), and Los Angeles (LA) abrasion in accordance with IS: 2386 Part IV (IS: 2386 Part IV, 1963). Prepared alkali-activated concrete specimens were tested for compressive strength, split tensile strength, and water absorption in accordance with Indian Standard, IS: 516 (IS: 516, 1959), IS: 5816 (IS: 5816, 1999). For performing compressive strength and water absorption, cube

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**Table 2. Details of mix proportions evaluated**

| Mix type | DBW (%) | Mixture type (kg/m^3) | NCA | NFA | CWA | BWA | FLA | GGBS | NaOH solution | Na_2 SiO_3 solution |
|----------|--------|-----------------------|-----|-----|-----|-----|-----|------|----------------|---------------------|
| AACWA0   | 0      | 1201 647 - - 286 122 41 103 |
| AACWA 25 | 25     | 901 485 300 162 286 122 41 103 |
| AACWA 50 | 50     | 601 323 601 323 286 122 41 103 |
| AACWA 75 | 75     | 300 162 901 485 286 122 41 103 |

Note: NaOH solution molarity was kept constant as 8 M

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Figure 2. Alkali-activated concrete mixing and specimen preparation (a) dry mix (b) wet mix (c) fresh mix in slump test (d) prepared specimens.
specimens of 150 × 150 × 150 mm were used. For split tensile strength, 150 mm diameter and 300 mm long cylinder specimens were used. Strength properties of specimens were determined in a standard compression testing machine. For each of the tests, three specimens were cast and air cured for 28 days at room temperature. The resistance to sulfuric acid for the AAC was conducted on cube specimens 100 × 100 × 100 mm dimension in accordance with ASTM C267 (ASTM ca. 2012). The specimens were air cured for 28 days at room temperature. Later, the specimens were completely submerged in 3% sulfuric acid solution. After submergence for a period of 3, 7, 14, and 28 days, the specimens were removed and gently cleaned with water to get rid of any loose particles before drying and weighting. The weight loss in individual specimens was used to assess the resistance to sulfuric acid solution.

3. Results and discussion

3.1. Properties of waste aggregates

Table 3 presents the properties of natural and waste aggregates. While, the obtained bulk density and specific gravity for waste aggregates is lower than natural aggregates, the water absorption and LA abrasion values are much higher. This trend can be attributed to the presence of porous mortar attached to CWA and the higher absorptive nature of BWA. Also, density values can get affected by the particle size distribution. Figure 3 indicates that the particle size distribution of natural aggregates show a well distribution in gradation curves, while the waste aggregates show some deviation when compared to natural aggregates. This difference can be attributed to the processing of waste aggregates in laboratory. For instance, NCA was crushed using mechanical

| Material | Bulk density (Kg/m³) | Specific gravity | Water absorption (%) | LA abrasion value (%) | Fineness modulus |
|----------|----------------------|------------------|----------------------|----------------------|------------------|
| NFA      | 1590                 | 2.40             | 2.85                 | -                    | 2.60             |
| NCA      | 1420                 | 2.55             | 1.10                 | 29                   | 4.09             |
| BWA      | 1325                 | 2.25             | 6.56                 | -                    | 2.12             |
| CWA      | 1125                 | 2.35             | 7.80                 | 42                   | 5.82             |

Figure 3. Particle size distribution of natural and waste aggregates.
crushers, while CWA was crushed manually. This has resulted the NCA to be much finer than CWA. Similarly, BWA gets crushed into fine particles easily. Therefore, the percent passing 75 μm sieve is higher (i.e., 11% as seen in Figure 3).

3.2. Workability and unit weight of AACWA
Alkali-activated concrete usually possess high viscosity due to the use of alkaline solutions. Even though the obtained slump values are high, the actual workability is still low (Nath & Sarker, 2014). Slump and unit weight tests were conducted in accordance with IS: 1199 (IS: 1199, 1959), and the results are shown in Figure 4. As seen, the slump values reduced with the inclusion of waste aggregates in AAC. For instance, the reduction in slump was 17.4%, 24%, and 43.5% for AACWA25, AACWA50, and AACWA75 mixes when compared to AACWA0 mix, respectively. One of the primary causes for such reduction is due to higher absorptive nature of porous mortar attached to CWA, as well as higher absorptive nature of BWA. The use of prewetted aggregates helped in restoring the workability. This is because prewetted aggregates contain water in their pores which can be available to some extent during mixing. Improvement in concrete workability due to the use of saturated surface dry and prewetted aggregates have been reported in the past (Nuaklong et al., 2016). Figure 4 shows the unit weight of AACWA. The reduction in unit weight of concrete with inclusion of waste aggregates was obvious, due to the low specific gravity and density values reported for waste aggregates. A maximum reduction of 6.5% in unit weight for AACWA75 was observed, when compared to AACWA0.

3.3. Compressive strength and split tensile strength of AACWA
The compressive strength of alkali-activated concrete is important to know, since it ensures the quality of the reactive products formed due to the alkali-activation process. Figure 5 shows the compressive strength of AACWA. It was observed that there was reduction in strength with addition of waste aggregates. Interestingly, the reduction was marginal (i.e., 8.6 %) for AACWA25, slightly higher (i.e., 36.9 %) for AACWA50, and substantially high (i.e., 78.5 %) for AACWA75, when compared to AACWA0, respectively. The low compressive strength for AACWA mixes can be attributed to presence of CWA and BWA. Higher content of BWA adversely affects the characteristics of the paste due to its low density. Also, reduction in concrete strength due to inclusion of crushed clay brick (Poon & Chan, 2006b), and the weakness of attached mortar in comparison to aggregate and new formed paste (Etxeberria et al., 2007), have been reported. Figure 6 shows the split tensile strength of AACWA. When compared to compressive strength, almost similar trends were observed for split tensile strength, wherein there was marginal reduction (i.e., 17.7%) for AACWA25, slightly higher (i.e., 45%) for AACWA50, and substantially high (i.e., 60.4%) for AACWA75, when compared to AACWA0, respectively. The average split tensile strength ranged 6% to 8% of the compressive strength for AACWA mixes, with an exception for AACWA75 which showed greater reduction in compressive strength. In order to understand the influence of BWA on strength of AAC, the results of present study were compared with past studies as shown in Figure 7, and corresponding details presented in Table 4. Nuaklong et al. (Nuaklong et al., 2016)
replaced natural coarse aggregate by 100% RCA. Shaikh (Shaikh, 2016) replaced natural coarse aggregate by RCA with replacement levels of 0%, 15%, 30% and 50% by weight. Hu et al. (Hu et al., 2019) replaced natural coarse aggregate with both crushed concrete and brick waste aggregates, at replacement levels of 0%, 50% and 100% by weight. As noticed, all the studies used natural sand as fine aggregate, which provided good strength for the hardened paste, and temperature curing enhanced the reaction mechanism and improved the mechanical properties of alkali-activated concrete. However, in this study the presence of BWA have detrimental effect on the strength of AACWA. Further, due to room temperature curing the enhanced reaction between alkaline activator and the vitreous component of FLA was not achieved completely. The mechanical properties of AACWA can be enhanced by temperature curing, because apart from FLA and GGBS, BWA are also rich in SiO₂ and Al₂O₃, which can take part in alkaline-activation process to
form Si-O-Al bonds (Komnitsas et al., 2015), but this was beyond the scope of this study, and further temperature curing will influence the practical feasibility of AACWA. Finally, it is interesting to note that AACWA25 and AACWA50 still possess enough strength to qualify for various civil engineering applications.

### 3.4. Water absorption and acid resistance of AACWA

The pore structure of alkali-activated concrete is very important, since it shall have direct influence on its durability. Therefore, it is important to understand the water absorption of AACWA, which is considered one of the relevant parameters influencing its performance. Figure 8 shows the water absorption of AACWA. In this study, all the specimens with waste aggregates exhibited higher water absorption values in comparison to one without waste aggregates. For instance, on average the water absorption values of AACWA25 was 1.54 times higher than AACWA0. Similarly, AACWA50 and AACWA75 exhibited 2.26 times and 2.83 times higher water absorption values than AACWA0, respectively. The increased water absorption for specimens with waste aggregates can be attributed to the higher absorptive nature of CWA and BWA. Also, these values get substantiated for AACWA75, which is a clear indication of less dense and openness of the hardened matrix, further resulting in low compressive strength. Almost similar trends were reported by Poon and Chan (Poon & Chan, 2006a), wherein, mixtures with 75% crushed bricks showed 2.52 times higher absorption values than the control mix. Also, CWA contains attached mortar which is porous in nature. The porous mortar in CWA act as a perfect channel for water to

**Figure 8. Water absorption of AACWA.**

| Sl. No. | Study | Alkaline activator | Precursor Material | Waste Aggregates | Curing condition | Curing duration |
|---------|-------|--------------------|--------------------|------------------|-----------------|----------------|
| 1       | Nukalong et al. (Nukalong et al., 2016) | NaOH & Na₂SiO₃ | 100% FLA | Nil | RCA | Heat cured at 60°C for 48 h and then room temp. | 28d |
| 2       | Shaikh (Shaikh, 2016) | NaOH & Na₂SiO₃ | 100% FLA | Nil | RCA | Steam cured at 60°C for 24 h and then room temp. | 28d |
| 3       | Hu et al. (Hu et al., 2019) | NaOH & Na₂SiO₃ | 70% FLA & 30% GGBS | Nil | RCA & BWA | Heat cured at 75°C for 24 h and then room temp. | 28d |
| 4       | Present, AACWA | NaOH & Na₂SiO₃ | 70% FLA & 30% GGBS | BWA | CWA | Room temp. | 28d |
flow through the hardened matrices and thereby influencing the water absorption and the volume of permeable voids (Hu et al., 2019). Figure 9 shows the percent weight loss of specimens when exposed to sulfuric acid solution. As seen, the initial weight loss is negligible, on average varying between 0.42 and 0.82% after 3d exposure. As time passes, the percent weight loss increases for all the mix types, but it is observed to be substantially high for AACWA75. For AACWA mixes the ingress of acid into the matrix through its porous medium causes leaching of unreacted sodium. Further, CWA contains cement mortar which has presence of calcium hydroxide, and sulfuric acid reacts with calcium hydroxide causing increased weight loss (Fernando & Said, 2011). This causes the average weight loss to be 2.67, 2.15, and 1.05 times higher for AACWA75, AACWA50, and AACWA25 when compared to AACWA0, respectively.

3.5. Benefits of AACWA

In order to understand the benefits of AACWA, economic analysis of the proposed concrete mix was performed. Cost comparison of AACWA with conventional concrete was studied. The conventional concrete mix proportion was based on IS 10262 (IS: 10262, 2009) to produce M30 grade of concrete, which is similar to the obtained 28-day compressive strength of AACWA25. Table 5 presents the details of the mix proportions along with material costs according to present market value, excluding transportation and other miscellaneous costs. As seen, the cost of AACWA25 was found to be 10% lower than that of the conventional cement concrete, which indicates that AACWA mixes can be produced at slightly lower cost, when compared to conventional cement concrete mixes.

Water scarcity in India is another ongoing crisis that affects many lives in the country each year. Therefore, saving water has become an important initiative for the government of India. The use of AACWA in precast industry (e.g., paver block manufacturing) can substantially reduce the water usage. For instance, the amount of water required for M30 grade cement concrete is 158 kg/m³ (as seen in Table 5). Whereas, the water required for making AACWA is dependent on the total quantity of alkaline solution used. In this study, the maximum amount of water used to prepare NaOH solution was 41 kg/m³, and for Na₂SiO₃ is (0.55 × 103) kg/m³, summing to a total of 98 kg/m³. This results in 38% less consumption of water for AACWA mixes in comparison to the cement concrete mixes. Further, additional water is utilized for curing of cement concrete, which is not required in case of AACWA. Therefore, the overall consumption of water for AACWA is much lower than the conventional concrete mixes, leading to substantial saving of water in the construction industry.

The monetary savings and conservation of natural resources are based on the mix proportions selected in this study, and actual values are subject to change according to the mix proportions adopted. Further, the main purpose in showing the benefits of AACWA is to encourage the field practitioners for its practical use in precast industry for non-structural applications. Also, this
method helps to mitigate problems faced in urban areas where there is lack of space to landfill the DBW and scarcity of natural aggregates from quarries.

4. Conclusions

In the current study, the possibility of using DBW as aggregates (coarse and fine) in AAC was evaluated. AACWA was made with FLA, GGBS, NaOH solution, Na$_2$SiO$_3$ solution, as well as natural coarse and fine aggregate composed of CWA and BWA in varying replacement rates, respectively. Fresh and hardened properties of the developed AACWA was determined using various standard methods. Based on experimental study following specific findings and conclusions can be enumerated.

(1) Incorporation of CWA and BWA as aggregates in AAC affects the workability negatively. Maximum and minimum slump of 230 mm and 130 mm was obtained for AACCWA0 and AACWA75, respectively. Higher absorptive nature of waste aggregates was the main reason for reduced workability. While, prewetting the waste aggregates for 24 hours helped in restoring the workability of AACWA mixes.

(2) The average 28-day compressive strength was 33.3, 30.4, 21, and 7.2 MPa for AACCWA0, AACWA25, AACWA50, and AACWA75, respectively. While, the average 28-day split tensile strength was 2.6, 2.14, 1.43, and 1.03 MPa for AACCWA0, AACWA25, AACWA50, and AACWA75, respectively. Both compressive strength and split tensile strength reduced proportionally up to 50% waste aggregate replacement, and very low compressive strength was obtained for AACWA75, suggesting detrimental effect of BWA on the strength of hardened AACWA.

(3) There was increase in water absorption and reduction to acid resistance for all AACWA mixes. The average 28-day water absorption was 5.36, 8.23, 12.09, and 15.16% for AACCWA0, AACWA25, AACWA50 and AACWA75, respectively. While, average reduction in specimen weight exposed to sulfuric acid solution for 28-day was 4.27, 4.49, 9.20, and 11.44% for AACCWA0, AACWA25, AACWA50, and AACWA75, respectively. This behavior was due to porous waste aggregates and presence of calcium hydroxide in mortar attached to CWA is prone to acid attack, affecting its stability and durability.

(4) Based on the findings of this study, AACWA25 and AACWA50 can be used in various civil engineering applications. Particularly, AACWA25 in non-structural applications such as footpaths and pedestrian facility is highly recommended.

### Table 5. Cost of conventional concrete versus AACWA

| Material | Quantity (kg/m$^3$) | Unit Cost (Rs/kg) | Total cost (Rs/m$^3$) | Material | Quantity (kg/m$^3$) | Unit Cost (Rs/kg) | Total cost (Rs/m$^3$) |
|----------|-------------------|------------------|----------------------|----------|-------------------|------------------|----------------------|
| Cement   | 288               | 6.5              | 1872                 | FLA      | 286               | 1.0              | 286                  |
| GGBS     | 72                | 2.5              | 180                  | GGBS     | 122               | 2.5              | 305                  |
| Water    | 158               | 0.22             | 35                   | NaOH solution | 41 | 25           | 1025             |
| NFA      | 798               | 0.7              | 559                  | Na$_2$SiO$_3$ solution | 103 | 8            | 824             |
| NCA      | 1113              | 0.7              | 780                  | NFA      | 485               | 0.7              | 340                  |
| Super plasticizer | 7.2 | 100        | 720                  | NCA      | 901               | 0.7              | 631                  |
| Total    | 4146              |                  | 3734                 | CWA      | 300               | 0.7              | 210                  |
|          |                   |                  |                      | BWA      | 162               | 0.7              | 113                  |

Note: 1 India Rupee (Rs) is equivalent to 0.013 US dollars.
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