Research Article

Potential Assessment of E-Waste Plastic in Metakaolin Based Geopolymer Using Petrography Image Analysis

Parth Verma,1 Priyanka Dhurvey,1 and Venkatesa Prabhu Sundramurthy2

1Department of Civil Engineering, MANIT, Bhopal 462003, Madhya Pradesh, India
2Department of Chemical Engineering & Center of Excellence for Bioprocess and Biotechnology, College of Biological and Chemical Engineering, Addis Ababa Science and Technology University, P.O. Box 16417, Addis Ababa, Ethiopia

Correspondence should be addressed to Parth Verma; parthverma1992@gmail.com and Venkatesa Prabhu Sundramurthy; venkatesa.prabhu@aastu.edu.et

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Abstract
Concrete’s binder can be substituted with rice husk ash, metakaolin, kaolin clay, GGBS, and other agricultural and industrial byproducts and waste materials, which lowers greenhouse gas emissions, namely carbon dioxide (CO2). When employed in the manufacturing of concrete, the aforementioned items reduce the amount of water required and have no discernible impact on the material’s long-term performance. Combination of metakaolin and class-F fly ash is taken for this experimental study to create geopolymer concrete, as both the materials are very good sources of aluminosilicates, which is the foremost requirement for the material to be the binder in geopolymer concrete. Also, the percentage replacement of crushed aggregates with crushed E-waste plastic (EWP) is to be incorporated in the MGPC. This study also uses the petrographic image analysis to validate the geopolymerization products forms in the MGPC and check the microstructure growth of geopolymerization of particles with age. The petrographic image analysis provides photographs of the microstructure of hydration products of the samples with good details. As the petrographic microscope is very affordable as compared to the SEM setup and requires less skilled worker, it comes out to be a good approach for the microstructural analysis.

1. Introduction
Davidovits’ geopolymer concrete technique assures that industrial and agricultural byproducts with rich in aluminates and silicates may be used effectively in place of cement as a substitute material for binder. Utilizing geopolymer technology might cut atmospheric CO2 emissions from the cement and aggregate sectors by roughly 80%. By substituting fly ash and metakaolin for cement as the binding agent, geopolymer concrete is gaining popularity as a sustainable building material [1–5].

E-waste consists of electrical and electronic devices that have been discarded and dumped. Approximately 85% of different electronic items are disposed of in landfills or incinerators, which might include or emit harmful substances in the environment, which will have an adverse effect on living beings and the environment. The excessive lead content of electronics alone causes harm to a person’s kidneys, blood, and central and peripheral neurological systems. Only 10–12 percent of existing e-waste is being recycled, and waste storage is a major issue in India. The
ideal method for using a coarse aggregate in concrete [6–13].

The petrographic examination is often carried out on rock samples to look into the morphology and past structures. Due to the clear visualization of microstructural pictures in a short amount of time, this study is garnering more interest in the examination of concrete and related materials. This observation provided a very detailed picture of the concrete’s paste structures and interface transition zones (ITZs) [14, 15].

2. Materials

2.1. Binders. The combination of metakaolin and class-F fly ash is taken into this experimental study as the source of alumino-silicate raw material. The specific gravity is calculated of fly ash is 2.52 and that of metakaolin is 2.24. These binder material’s compositions of chemical oxides are presented in tabular form, i.e., Table 1.

| S. No. | Oxide composition | Metakaolin (class-M) | Fly ash (class-F) |
|--------|------------------|----------------------|------------------|
| 1      | Silicon oxide (SiO$_2$) | 51.59                | 49.90            |
| 2      | Aluminum oxide (Al$_2$O$_3$) | 43.13              | 29.70            |
| 3      | Ferrous oxide (Fe$_2$O$_3$) | 2.41                | 10.90            |
| 4      | Calcium oxide (CaO) | 1.78                 | 3.11             |
| 5      | Potassium oxide (K$_2$O) | 0.73                | 0.90             |
| 6      | Magnesium oxide (MgO) | 0.72                | 1.30             |

2.2. Alkaline Liquid. The geopolymerization in the concrete is performed only when the binder materials get activated in the alkaline solution. NaOH and Na$_2$SiO$_3$ solution is used as alkaline liquid.

2.3. Aggregates. Aggregates with different types and size are used in this study, starting from basaltic aggregates of maximum size 20 mm, basaltic crushed aggregates, and e-waste plastic of maximum size 10 mm and locally available Narmada river fine aggregates. The physical characteristics of these aggregates are show in Table 2.

3. Test Methodology

3.1. Test Parameters. The experimental tests are conducted to perform the studies on various mix design parameters of metakaolin-based geopolymer concrete including the metakaolin to fly ash ratio, NaOH molarity, percentage of e-waste plastic as replacement of crushed aggregates, NaOH to Na$_2$SiO$_3$ ratio and alkaline liquid to binder ratio. In the context of restricted research on metakaolin-based geopolymer concrete, the ranges established for each parameter tested are chosen. The test matrix for this research work is developed using a reference mix that the authors had obtained after a number of trials to create a mix design with good mechanical strength.

3.2. Casting. For around 5 minutes, an electric concrete mixer is operated to mix all of the dry raw materials, including coarse and crushed aggregates, e-waste plastic, fine aggregates, metakaolin, and fly ash. After that, alkaline liquid is gradually added into the operating mixer with dry raw materials until a homogeneous mix is formed. The geopolymer mix is then moulded into conventional cube moulds of sizes 150 mm in diameter, 300 mm tall cylindrical moulds, and beam moulds of size 100 mm × 100 mm × 500 mm, after which it is vibrated on a vibrating table. Also, in the same manner, reference normal cement concrete samples are casted.

3.3. Curing. The samples are demoulded after 24 hours and put inside hot air over at 60°C for 72 hours straight away and then cured at normal temperature for 7, 14, and 28 days. Similarly, the normal cement concrete samples are cured under water for 7, 14, and 28 days.

3.4. Experimental Programme. All mixtures’ mechanical characteristics are assessed using the standard IS-codal provisions. To evaluate the workability of various blends, the conventional slump test is used. After 28 days, the hardened density of the concrete specimens is evaluated for various e-waste plastic content percentages. The investigated mechanical parameters include the test of compressive strength after a period of 7 days than 28 days and also, the test of splitting tensile and flexural strength after 28 days for different values of test parameters [8, 16–19].

Table 3 shows the variations in the test parameters adopted for this research work.

4. Results and Discussion

4.1. Crushing Strength. Tables 4–7 depict that the crushing strength is directly dependent and related to the molarity of the NaOH solution, as the molarity is increasing, and the cube crushing strength is also on the increasing side. Similarly, the Na$_2$SiO$_3$ to NaOH ratio also has the direct relation with the crushing strength, as the ratio is increased, the resistance to crushing under UTM is also increased, up to a certain limit, i.e., beyond the ratio 3, the mix becomes very sticky and cannot be moulded and sets while mixing.

Also, from Tables 4–7, it is evident that the binder ratio of 60% metakaolin and 40% fly ash works the best with the low molar alkaline solutions used in this research. The 100% metakaolin mix sets within 5 seconds of adding the alkaline liquid and hence, cannot produce a workable mix and similarly, the 100% fly ash mix does not set with low molarity alkaline liquid and leads a failed mix.

From Table 8, the optimum ratio of NaOH is as follows: Na$_2$SiO$_3$ and the molarity is 1 : 3 and 10 M, respectively. So, the MC15 mix is finalized for further study.

4.2. Split Tensile Strength. The results from Tables 9 and 10 are in accordance with the crushing strength test results and hence, the binder ratio, molarity of the alkaline liquid, and
Table 2: Aggregate properties.

| S. No. | Aggregate type               | Fineness modulus | Water absorption (%) | Specific gravity |
|--------|------------------------------|------------------|----------------------|------------------|
| 1      | Coarse (max. size = 20 mm)   | 6.58             | 1.02                 | 2.62             |
| 2      | Crushed (max. size = 10 mm)  | 6.42             | 0.97                 | 2.68             |
| 3      | E-waste plastic (max. size = 10 mm) | 6.10         | 0.10                 | 1.10             |
| 4      | Narmada sand (locally available) | 2.74             | 2.20                 | 2.58             |

Table 3: Test parameters.

| S. No. | Parameter                     | Remark                                               |
|--------|-------------------------------|------------------------------------------------------|
| 1      | Binder ratio                  | Metakaolin to fly ash ratio (by mass)               |
| 2      | Alkaline liquid molarity      | Molarity of NaOH solution                            |
| 3      | Alkaline liquid ratio         | NaOH to Na₂SiO₃ ratio (by volume)                    |
| 4      | E-waste plastic percentage   | % Replacement of EWP as crushed aggregate           |

Table 4: Cube crushing strength test of mix with 8 M solution (1 : 2.5).

| Mix   | Binder ratio                  | 7th day (N/mm²) | 28th day (N/mm²) |
|-------|------------------------------|-----------------|------------------|
| MC1   | 80% MK + 20% FA              | 29.11           | 29.69            |
| MC2   | 70% MK + 30% FA              | 29.81           | 30.88            |
| MC3   | 60% MK + 40% FA              | 32.21           | 32.97            |
| MC4   | 50% MK + 50% FA              | 30.08           | 30.54            |

Table 5: Cube crushing strength test of mix with 8 M solution (1 : 3).

| Mix   | Binder ratio                  | 7th day (N/mm²) | 28th day (N/mm²) |
|-------|------------------------------|-----------------|------------------|
| MC5   | 80% MK + 20% FA              | 25.64           | 30.88            |
| MC6   | 70% MK + 30% FA              | 29.36           | 31.42            |
| MC7   | 60% MK + 40% FA              | 31.30           | 32.99            |
| MC8   | 50% MK + 50% FA              | 30.89           | 31.02            |

Table 6: Cube crushing strength test of mix with 10 M solution (1 : 2.5).

| Mix   | Binder ratio                  | 7th day (N/mm²) | 28th day (N/mm²) |
|-------|------------------------------|-----------------|------------------|
| MC9   | 80% MK + 20% FA              | 29.65           | 30.73            |
| MC10  | 70% MK + 30% FA              | 31.55           | 31.97            |
| MC11  | 60% MK + 40% FA              | 32.43           | 33.09            |
| MC12  | 50% MK + 50% FA              | 32.11           | 32.96            |

Table 7: Cube crushing strength test of mix with 10 M solution (1 : 3).

| Mix   | Binder ratio                  | 7th day (N/mm²) | 28th day (N/mm²) |
|-------|------------------------------|-----------------|------------------|
| MC13  | 80% MK + 20% FA              | 29.91           | 31.40            |
| MC14  | 70% MK + 30% FA              | 31.79           | 32.19            |
| MC15  | 60% MK + 40% FA              | 32.84           | 33.38            |
| MC16  | 50% MK + 50% FA              | 31.76           | 32.28            |

Table 8: Compressive strength comparison.

| Mix   | 28th day (N/mm²) |
|-------|------------------|
| MC3   | 32.97            |
| MC7   | 32.30            |
| MC11  | 33.09            |
| MC15  | 33.38            |

Table 9: Split tensile strength test of mix with 8 M solution at 28 days.

| No.   | Binder ratio                  | 1 : 2.5 | 1 : 3    |
|-------|------------------------------|---------|---------|
| 1     | 80% MK + 20% FA              | 2.82    | 2.74    |
| 2     | 70% MK + 30% FA              | 3.03    | 3.34    |
| 3     | 60% MK + 40% FA              | 3.15    | 3.22    |
| 4     | 50% MK + 50% FA              | 3.06    | 3.12    |
Table 10: Split tensile strength test of mix with 10M solution at 28 days.

| S. No. | Binder ratio | 1:2.5 | 1:3 |
|--------|--------------|-------|-----|
| 1      | 80% MK + 20% FA | 2.86  | 2.99|
| 2      | 70% MK + 30% FA | 3.15  | 3.14|
| 3      | 60% MK + 40% FA | 3.59  | 4.03|
| 4      | 50% MK + 50% FA | 3.22  | 3.37|

Table 11: Flexural strength test of mix with 8M solution at 28 days.

| S. No. | Binder ratio | 1:2.5 | 1:3 |
|--------|--------------|-------|-----|
| 1      | 80% MK + 20% FA | 2.75  | 3.17|
| 2      | 70% MK + 30% FA | 3.08  | 4.02|
| 3      | 60% MK + 40% FA | 3.47  | 4.37|
| 4      | 50% MK + 50% FA | 3.19  | 3.82|

Table 12: Flexural strength test of mix with 10M solution at 28 days.

| S. No. | Binder ratio | 1:2.5 | 1:3 |
|--------|--------------|-------|-----|
| 1      | 80% MK + 20% FA | 3.11  | 3.17|
| 2      | 70% MK + 30% FA | 3.13  | 4.06|
| 3      | 60% MK + 40% FA | 3.69  | 3.16|
| 4      | 50% MK + 50% FA | 3.36  | 3.77|

Table 13: Compressive strength test for different of % EWP.

| Mix    | Percentage of EWP as replacement of crushed Agg. | 3rd day (N/mm²) | 7th day (N/mm²) | 28th day (N/mm²) | % Drop |
|--------|-----------------------------------------------|-----------------|-----------------|------------------|--------|
| MC15   | 0                                             | 18.37           | 29.39           | 36.74            | —      |
| MC15-5 | 5                                             | 18.27           | 29.23           | 36.54            | 0.544  |
| MC15-10| 10                                            | 15.06           | 24.10           | 30.12            | 18.02  |
| MC15-15| 15                                            | 14.16           | 22.66           | 28.32            | 22.92  |

Table 14: Split tensile strength test for different of % EWP.

| Mix    | Percentage of EWP as replacement of crushed Agg. | 3rd day (N/mm²) | 7th day (N/mm²) | 28th day (N/mm²) | % Drop |
|--------|-----------------------------------------------|-----------------|-----------------|------------------|--------|
| MC15   | 0                                             | 1.56            | 2.50            | 3.12             | —      |
| MC15-5 | 5                                             | 1.46            | 2.34            | 2.92             | 0.610  |
| MC15-10| 10                                            | 1.31            | 2.10            | 2.62             | 16.09  |
| MC15-15| 15                                            | 1.18            | 1.88            | 2.35             | 24.73  |

Table 15: Flexural strength test for different of % EWP.

| Mix    | Percentage of EWP as replacement of crushed Agg. | 3rd day (N/mm²) | 7th day (N/mm²) | 28th day (N/mm²) | % Drop |
|--------|-----------------------------------------------|-----------------|-----------------|------------------|--------|
| MC15   | 0                                             | 2.02            | 3.23            | 4.04             | —      |
| MC15-5 | 5                                             | 1.74            | 2.78            | 3.47             | 14.11  |
| MC15-10| 10                                            | 1.58            | 2.53            | 3.16             | 21.74  |
| MC15-15| 15                                            | 1.39            | 2.22            | 2.78             | 31.33  |
Table 16: Water absorption for different of % EWP.

| Mix      | Percentages of EWP as replacement of crushed Agg. | W1 (kg) (oven dry) | W2 (kg) (saturated surface dry) | Percentage of water absorption | Percentage of drop |
|----------|--------------------------------------------------|-------------------|---------------------------------|-------------------------------|--------------------|
| MC15     | 0                                                 | 8.374             | 8.757                           | 4.57                          | —                  |
| MC15-5   | 5                                                 | 8.028             | 8.367                           | 4.22                          | 0.76               |
| MC15-10  | 10                                                | 7.699             | 8.005                           | 3.97                          | 13.13              |
| MC15-15  | 15                                                | 7.353             | 7.594                           | 3.28                          | 28.23              |

Table 17: Workability test for different of % EWP.

| Mix      | Percentages of EWP as replacement of crushed Agg. | Slump (mm) | IS code range | Remark |
|----------|--------------------------------------------------|------------|---------------|--------|
| MC15     | 0                                                 | 43         | 0–50          | Low    |
| MC15-5   | 5                                                 | 68         | 50–100        | Medium |
| MC15-10  | 10                                                | 87         | 50–100        | Medium |
| MC15-15  | 15                                                | 104        | 100–150       | High   |

Table 18: Hardened density for different of % EWP.

| Mix      | Percentages of EWP as replacement of crushed Agg. | W1 (kg) (oven dry) | Density (kg/m³) |
|----------|--------------------------------------------------|-------------------|-----------------|
| MC15     | 0                                                 | 8.374             | 2481.19         |
| MC15-5   | 5                                                 | 8.028             | 2378.67         |
| MC15-10  | 10                                                | 7.699             | 2281.19         |
| MC15-15  | 15                                                | 7.353             | 2178.67         |

Figure 1: Petrographic image using a 4x lens of normal concrete at 28th day.
the NaOH. The Na$_2$SiO$_3$ ratio is same as concluded previously.

4.3. Flexural Strength. The results from Tables 11 and 12 again show the same trend in the results as seen in the compressive strength results. Hence, the binder ratio, molarity of the alkaline liquid, and the NaOH. The Na$_2$SiO$_3$ ratio is same as concluded previously.

4.4. Mixes with E-Waste Plastic

4.4.1. Mechanical Strength. The inclusion of EWP in the geopolymer concrete mix MC15, as partial replacement of crushed aggregates (max. size 10 mm), is checked for different percentages of EWP.

Table 13 shows that the drop in the compressive strength is very significant in the MC15 mix, if EWP is added beyond 5%. Similarly, Tables 14 and 15 also prove...
the same point that replacement over 5% of EWP results in a very steep drop in the split tensile and beam (flexural, i.e., moment resisting) strength. The reason behind the drop in strength with increment in the percent of EWP is because the main strength of concrete is derived from the aggregates, as the EWP do not provide the strength as provided by the conventional aggregates, hence, the strength is reduced.

4.4.2. Water Absorption, Workability, and Hardened Density. Water absorption is a major aspect of any material to be used as an aggregate. The EWP absorbs a negligible amount of water as plastic is hydrophobic in nature, as shown in Table 2. Table 16 shows the result in accordance with the above-mentioned reasoning, as the percentage of EWP is increasing in the mixes, and the water absorption of the set cube after 28 days is decreasing.

Workability of the geopolymer mixes is shown in Table 17. The finalized mix MC15 produces low workability, but when the EWP is added into the mix, workability is increases with the percentage increase in the EWP. The prominent cause for the increased workability of the mixes with EWP is that it absorbs negligible the amount of water from the mix and also, floats over the water; due to low density, the mixes become more workable.

Figure 4: Normal concrete % gelation at the 28th day.

Figure 5: MC15-5 mix % gelation at the 7th day.
Table 18 shows the hardened density results of the mixes after 28 days, and with no surprise, the density of the mixes is on the decreasing side as the EWP percentage is increasing in the mix. The density of the EWP is very low as compared to the conventional aggregates; hence the overall density of the set mixes is low.

The mix MC15-5 is selected as the optimum mix for the metakaolin base geopolymer concrete with EWP, as the 5% replacement of crushed aggregates with EWP provides good results with respect to strength, workability, water absorption, and hardened density. The strength is the main criteria here to select the EWP percentage in concrete.

4.5. Finalized Parameters. The series of experiments, under the scope of this research work, provided the substantial data to finalize the parameter of the metakaolin-based geopolymer concrete with EWP.

4.6. Petrographic Image Analysis. The petrographic image analysis is a convenient way to derive the relationship between the crystals of the mix and the geopolymerization products. The shape, size, and frequency of the geopolymerization products can be measured by using a microscope and software. The arrangement of 4x, 10x, and 40x lenses makes it more reliable and efficient to determine the accurate shapes and boundaries of the final mix products.

The slides and thin rock samples of the mixes are prepared and analyzed under the microscope, and the measurements were taken using the ToupView software.

Figure 1 provides an image of the thin section of the petrography image of hardened concrete is prepared after 28 days. This image demonstrates the microstructure development after hydration.

(i) Major portion of concrete consists C–S–H (calcium silicate hydrates), which constitutes around 70% of the volume of solids which is responsible for the higher strength.

(ii) Ca(OH)\(_2\) (calcium hydroxide) crystals, represented by hexagonal morphology which constitutes around 20% of the volume of solids.

(iii) C-A-S-H (calcium alumino silicate hydrates) are needle shaped prismatic crystals. C-A-S-H constitutes around 7% of the volume of solids in the hydrated concrete.

Figure 2 shows the thin section of the petrography image of the hardened MC15-5 mix is prepared after 28 days. This image demonstrates the microstructure development after geopolymerization.

(i) Fly ash (class-F) and metakaolin, which have higher content of silica and alumina have low in calcium, may be alkaline activated to produce the major reaction, i.e., geopolymerization product, called as N-A-S-H (sodium alumino silicate hydrates) gel, also known as geopolymer gel.

(ii) The geopolymer’s N-A-S-H gel regulates the strengths of the material, i.e., cube crushing, tensile, or moment bearing flexural strength. A better mix and, consequently, a decrease in porosity are seen when the silicate to the alumina ratio is raised. This demonstrates that the same factors that increase the geopolymers’ strength are also those that make the material less porous and, thus, less permeable.

The petrographic image analysis is used here to calculate the percentage gelation of the normal concrete mix and MC15-5 mix after 7 and 28 days. The geopolymer concrete
always has the advantage over conventional cement concrete in gaining the early strength. The reason of early strength of geopolymer concrete is the fast gelation due to alkaline activators which are not there in normal concrete. The total area of the image taken by the ToupView software for analysis is 242950 μm².

Figure 3 and 4 show the hydration gel formation in the normal concrete at the 7th and 28th day, respectively. The marked area with green boundary is the C–S–H gel, having a total area of 44506 μm², which is about 18.32% of the total area, in Figure 3. The marked area with blue boundary is the voids and unreacted binders in the sample i.e., cement concrete. Now, the area of the C–S–H gel at the 28th day is 214844 μm², which is about 88.43% of the total area, in Figure 4.

Figures 5 and 6 show the geopolymer gel formation in the MC15-5 mix at the 7th and 28th day, respectively. The marked area with the blue boundary is the voids and unreacted binders. Now, the total area of the geopolymer gel is calculated as 196733 μm², which is 80.98% of the total area, at the 7th day, in Figures 5 and 224798 μm², which is 92.53% of the total area, at the 28th day, in Figure 6.

The percentage gelation at the 28th day is nearly same for both normal concrete and MC15-5 mix. But main difference is in the percentage gelation at the 7th day. The MC15-5 mix clearly outperforms the conventional concrete with 81% gelation, as compared to 18% gelation of the normal concrete.

Hence, the petrographic image analysis clearly shows the reason behind the early strength gaining of geopolymer concretes by showing the gelation percentages at different stages.

5. Conclusions

In the study described in the present work, the influence and relation of mix design parameters (metakaolin to fly ash ratio, NaOH molarity, alkaline liquid to binder ratio, NaOH to Na₂SiO₃ ratio, and percentage of e-waste plastic as replacement of crushed aggregates) on metakaolin-based geopolymer concrete with e-waste plastic is explored. Mechanical strengths (crushing, moment resisting, and splitting tensile strength), hardened density, workability, and water absorption are the parameters that are examined. Two normal cement concrete mixes for reference and twenty geopolymer mixes were tested. The outcomes of this research are summarized as follows:

(i) The binder ratio i.e., metakaolin to fly ash (class-F) ratio also affects the strength properties of the geopolymer concrete. The quick setting phenomenon of the metakaolin bars is to be used alone as a binder. Similarly, the slow rate of reaction of fly ash makes it very difficult to set quickly after casting. Hence, the optimum ratio of both MK and fly ash is evaluated, i.e., 60 : 40, by mass, for the better performance of geopolymer concrete.

(ii) The cube crushing, split tensile, and moment resisting (flexural) strengths are directly related to the molarity and amount of silicates in the alkaline liquid. As per the experimental data, the molarity of the NaOH was increased from 8M to 10M, and also, the Na₂SiO₃ to NaOH ratio was increased from 2.5 to 3, by volume, the mechanical strength in all the three test was increasing.

(iii) The percentage of E-waste plastic included in the mix reduces the strength of the geopolymer concrete. But up to 5% replacement of crushed aggregate can be done without having much deterioration in the strength properties, and also, it improves the durability aspect of the geopolymer concrete, i.e., the workability is increased from low to medium, water absorption is dropped by around 7%, and the hardened density is also reduced, making it a light weight mix as compared to conventional concrete.

(iv) The petrographic image analysis (PIA) provides the clear images for the microstructural study of the concrete, and also, it helped to determine the geopolymerization products in the hardened mix. The ToupView software provides the tools to evaluate the gelation percentage and boundary markings for shape and size determination of the geopolymerization end products, such as C-A-S-H gels, C–S–H gels, and N-A-S-H gels. It proves to be the best and affordable alternate to SEM (scanning electron microscope) Analysis.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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