Calculation formula in determining recycling of disposable diapers waste as concrete composite materials

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Abstract. Disposable diaper waste is a crucial environmental problem today. Population growth is one of the triggers for increasing this type of waste. To overcome this, various studies on recycling diaper waste are a top priority. Some researchers recycle diaper waste as building components, especially concrete. The results of those studies have a positive impact on waste recycling innovation. In this paper, we will try to approach the formula for calculating the recycling of diapar waste as concrete. In addition, a simple simulation is used to determine the capacity of diaper waste that can be recycled as building material. The study revealed that parameters to calculate waste capacity for disposable diapers is age population of 0-4 years, frequency of changing diaper and mass of diaper. Thus, parameters to be considered for replacement of concrete component by waste materials, especially disposable diapers is density of materials, mass of materials and percentage of replacement. Based on the calculation simulation results, the use of diaper waste as a concrete material for road pavement is better to reduce waste production capacity than for building components.

1. Introduction
Population growth in the world currently reaches 7 billion and is predicted to increase to 10 billion by 2040 [1]. This population growth causes several environmental problems due to the consumption of natural resources to meet human needs such as land use, water, and energy [1]. In the term of environmental waste management, the population growth in the world leads to the increase of disposable diaper usage in the term of baby nursing. Disposable diapers become more popular since it was introduced in the 1960s due to the benefit of the circular economy within several versions of diapers and modified for a wider range of applications over the years [2]. While another benefit is in the social aspect, especially the convenience for parents by offer performances and affordability.

Beside it gives beneficial aspect of economy and social, in the term of waste management system, it also increases the difficulty of disposing and recycling once the diapers have been used and turned into waste. Currently disposable diapers contribute up to 4% from the total of solid waste and this amount has been increasing over the years [3]. Moreover, approximately 20 billion disposable diapers are thrown into landfills every year or more than 3.5 million tonnes of waste [4]. Based on a survey of
household preferences for disposing of disposable diapers, around 5-40% of this waste is disposed of in landfills without further processing [5]. It leads to another problem of health.

Disposable diapers contain dioxins and dyes, as cancer agents that if released into the environment it can be accumulated in human and animals. Landfill causes serious environmental problems such as methane emissions, water pollution, land use, and odors [6-7]. Disposable diapers are also not degraded very well, it takes 500 years for nature to decompose them [8]. Furthermore, people often dispose of it wrapped in plastic [9-10]

In the term of infrastructure development, the material innovation that involved nondegradable waste material also become main focus in several research, especially to recycle disposable diapers waste as concrete components. The research proof that for mechanical properties and microorganism content, the disposable diaper concrete has no significant distinction with normal concrete [8] [11-12]. In addition, comparing to other waste management such as incineration and co-firing, by recycling disposable diapers as concrete components has more benefit in term of carbon emission and eco-costs [13]

However, the problem comes up when calculating the exact waste capacity of disposable diapers that may solved by recycling as concrete components. This paper is explained the calculation by using case study of urban city in Bandung, Indonesia. The study is conducted by collecting data of disposable diapers usage in Bandung, then using calculation approach of concrete mix design to assume the replacement component capacity of concrete that filled by disposable diapers waste. The final calculation is to assume the capacity of disposable diapers concrete that benefit to use as infrastructure materials, such as building components and road pavement.

2. Methods

2.1. Parameters Approach

To assume the disposable diapers waste capacity, some parameters are used. Some literatures state that the use of disposable diapers in household depends on background of parent such as age and sex [20][22][24], education [5][10][22], marital status [20], job and income [5][20][22-24]. While the main parameter is background of children such as age and sex [5][19-23], breast feeding [25-29] and toilet training [5][22-23][25-26][29-30]. These parameters have a relation to the usage of disposable diapers daily.

| Age of baby | Diapers Use Frequency | Source |
|-------------|-----------------------|--------|
| 0 - 12 months | 2 - 6 times per day | [31] |
| 0 - 4 years | 11 - 15 times per week = 2 - 3 per day | [5] |
| 0 - 3 years | 2 - 10 times per day | [30] |
| 0 - 6 months | 1 - 6 per day | [26] |
| 0 - 1 month | 3 - 9 times per day | [27] |
| 0 - 1 month | 3 - 8 times per day | [28] |
| 0 – 14 month | 5 – 9 times per day | [32] |

Based on the equation (1), then the weight of diapers can be decided 30.06 gr per piece. This parameter then marked as $md$ (mass of diapers).

After all parameters decided, then to calculate the waste capacity of diapers per day is determined by population of age 0-4 years ($Pb$), frequency of diapers usage daily, monthly, or annual ($Fd$) and mass of diapers per piece ($md$) as formulized in the equation:

Based on table 1, the range frequency of children from 0 – 4 years age is 1 to 10 times of changing diapers a day. In this study the frequency is assumed based on simple equation:
Average = \frac{\sum_{n1}^{n2}}{n} \quad (1)

Where \( n1 \) and \( n2 \) are the lowest and the highest value of the data. \( N \) is total data. Based on the equation, the average of children changing the diapers is 5 times or piece a day. This parameter then marked as \( Fd \) (frequency of diapers).

The other parameter to set in this calculation is weight of disposable diapers that show in Table 2

| Quantity | Weight       | Source          |
|----------|--------------|-----------------|
| 12 pc    | 318.2 - 429.6 gr = 26.5 – 35.8 gr | [33][34]        |
| 1 pc     | 26.5 - 27.4 gr                  | [32][34]        |
| 1 pc     | 28.04 - 36.1 gr                  | [34]            |

Based on the equation (1), then the weight of diapers can be decided 30.06 gr per piece. This parameter then marked as \( md \) (mass of diapers).

After all parameters decided, then to calculate the waste capacity of diapers per day is determined by population of age 0-4 years (Pb), frequency of diapers usage daily, monthly, or annual (Fd) and mass of diapers per piece (md) as formulized in the equation (2) where \( Cd \) is marked as capacity of waste diapers.

\[ Cd = Pb \times Fd \times md \quad (2) \]

2.2. Concrete Mix Design Approach

Based on several studies, the disposable diapers in concrete act as a substitute for fine aggregate. However, the replacement of fine aggregate by disposable diapers is to be considered in term of density distinction. To meet apple to apple of weight ratio, this calculation involves the formula:

\[ \rho = \frac{m}{V} \quad (3) \]

Where:

\( \rho \) = density of material (gr/cm³)
\( m \) = mass or weight of material (gr)
\( V \) = volume or three-dimensional space (cm³)

In this scenario, the ratio of fine aggregate (fa) and disposable diaper (dd) is mutual in the volumetric. So, the calculation is decided by:

\[ \frac{V_{fa}}{\rho_{fa}} : \frac{V_{dd}}{\rho_{dd}} \quad (4) \]

Then the mass of disposable to replace fine aggregate in the concrete mix design is determined:

\[ md = \% rep \times \left( \frac{\rho_{d}}{\rho_{fa}} \right) \times m_{fa} \quad (5) \]

Where:

\( \rho_{d} \) = density of disposable diaper (gr/cm³)
\( md \) = mass or weight disposable diaper (gr)
\( \rho_{fa} \) = density of fine aggregate (gr/cm³)
\( m_{fa} \) = mass or weight of fine aggregate (gr)
\( \% rep \) = replacement percentage of fine aggregate by disposable diaper (%)

For density of disposable diapers is 0.07 - 0.21 g/cm³ [35]. Then, by incorporate the equation (2) to equation (5), the equation of diaper capacity that can be used for concrete components is obtained:

\[ Cdc = \frac{(Pb \times Fd \times md)}{\% \ rep \times \left( \frac{\rho_{d}}{\rho_{fa}} \right) \times m_{fa}} \quad (6) \]

Then Cdc is marked as capacity of disposable diapers concrete that can be produced.
3. Result and discussion

3.1. Case study preview

Due to the population growth becoming the main issue of waste production, this case study involved metropolitan cities in Indonesia. The other criteria in determining case study is population age of 0-4 years old, because the waste production for disposable diapers derived from this population. Another one is waste management in the case study, how the government or local communities deal with the waste production. These criteria for selected cities are compiled from secondary data based on Indonesian Municipal Central Bureau of Statistics (BPS).

Based on the criteria, Bandung is appropriate to be the selected city due to the available information that provide in Table 3.

Table 3. Comparative selection criteria for case study

| No. | Metropolitan Cities | Population | Population Age 0-4 | Waste Production | Waste Treatment | Source |
|-----|---------------------|------------|--------------------|------------------|----------------|--------|
| 1   | East Jakarta        | 3 037 100  | 238 497            | not available    | not available  | [14]   |
| 2   | Bekasi              | 3 003 900  | not available      | not available    | not available  | [15]   |
| 3   | Surabaya            | 2 896 000  | 183 975            | not available    | not available  | [16]   |
| 4   | Bandung             | 2 507 900  | 182 116            | 66 472 340       | Categorised    | [17]   |
| 5   | West Jakarta        | 2 434 500  | 184 826            | 67 461 490       | Not Identify   | [18]   |

Table 4. Waste Type Separation in Bandung [17]

| Garbage Type                | (M3/Day) | Percentage % |
|-----------------------------|----------|--------------|
| Food waste and leaves       | 772.69   | 44.51%       |
| Woods and twigs             | 69.09    | 3.98%        |
| Paper                       | 227.76   | 13.12%       |
| Plastic                     | 324.28   | 18.68%       |
| Metal                       | 15.62    | 0.90%        |
| Cloths                      | 82.46    | 4.75%        |
| Rubber and leather          | 41.32    | 2.38%        |
| Hazardous waste             | 131.42   | 7.57%        |
| Others                      | 71.35    | 4.11%        |
| **Total**                   | 1 735.99 | 100.00%      |

Based on population criteria, Bandung is fourth rank the most populous city in Indonesia. Compared to other populous cities, the information waste management in Bandung also available. Table 2 shows the garbage type that currently separated in municipal solid waste of Bandung. For disposable diapers waste, there is still categories to other type of garbage. Unlike other categories such as plastic, cloth or metal which have value to be recycled, disposable diaper is still unvaluable. The waste will be ended up in the incineration system. The recycling idea for disposable diapers will be triggered the government or society to separate the waste and turn it into new valuable items.

3.2. Calculation approach based on case study

To calculate the volume of diaper waste that can be recycled into building components, a concrete mix design calculation approach is based on Indonesian National Standard (SNI) 7394:2008 The Procedure for Calculating the Unit Price of Concrete Work for Building and Housing Construction. It should be noted that the use of concrete mix design in this case study is only for simplifying calculations. For more valid mix design results, it is necessary to carry out further laboratory tests, such as tests for aggregates and other mixed materials for concrete.

In this study, the concrete was designed in high strength of K-300 with the composition for 1 m³ concrete is 413 kg coarse aggregate, 1021 kg fine aggregate and 681 kg Portland cement. The
disposable diapers is replacement for fine aggregate. The optimal percentage of replacement is 5% to 10% addition to reach the optimal compressive strength [8][11-12].

According to equation (2) and (5), the capacity of waste disposable diapers in case study is determined:

\[ P_{b} = 182116 \text{ people (pc)} \]
\[ F_{d} = 5 \text{ pc/day} \]
\[ m_{d} = 30.06 \text{ gr/pc} \]
\[ \rho_{d} = 1400 \text{ kg/m}^{3} \text{ (middle range)} \]
\[ \rho_{fa} = 2082 \text{ kg/m}^{3} \]
\[ m_{fa} = 681 \text{ kg} \]
\[ \% \text{ rep} = 7.5\% \text{ (middle range)} \]

Then the capacity of waste disposable diaper in Bandung can be determined based on equation (7) as:

\[ C_{d} = P_{b} \times F_{d} \times m_{d} \quad (7) \]
\[ C_{d} = 27372 \text{ kg/day} = 19.56 \text{ m}^{3}/\text{day} \]

Then the capacity of recycled disposable diapers for 1 m³ concrete component is based on equation (8)

\[ m_{d} = \% \text{ rep} \times \left( \frac{\rho_{d}}{\rho_{fa}} \right) \times m_{fa} \quad (8) \]
\[ m_{d} = 34.35 \text{ kg} = 0.025 \text{ m}^{3} \]

Then, capacity of disposable diapers concrete that can be produced in Bandung is determined by equation (6) is 796.99 m³.

Next the author tries to simulate the calculation of this diaper concrete production with a design proposal for a type 36 housing with the standard structure shown in the following table 5.

The table shows the capacity of diaper concrete that can be used to build a housing of type 36, which is 48.15 m³. By considering the daily production of diaper concrete, which is 796.99 m³, approximately 16 units of type 36 houses can be obtained. In addition, the author tries to simulate the disposable diapers concrete as road pavement. The calculation by designing a 4 m wide pavement with a thickness of 20 cm and the result is 0.997 km of road pavement can be constructed. However, it is noted that this calculation is for daily diaper waste production, if it is calculated in monthly or yearly terms, there will be even more amount of diaper waste that must be added recycled into building components or road pavements.

**Table 5. Design simulation of housing type 36**

| Building component | Dimension (m) | Unit | *DDC (m³) |
|--------------------|---------------|------|-----------|
| Colom              | 0.3 x 0.3 x 3 | 9    | 2.43      |
| Beam               | 0.3 x 0.4 x 3 | 12   | 4.32      |
| Wall Panel         | 3 x 3 x 0.05  | 12   | 5.4       |
| Floor              | 6 x 6          | 1    | 36        |
| **Total DDC per housing unit of type 36** |                |      | **48.15** |

DDC = disposable diapers concrete

Based on those simple simulation and calculation approach, this paper is recommended for recycling the disposable diapers as concrete component, it would be more effective as road pavement that housing component.

4. Conclusion

- Parameters to calculate waste capacity for disposable diapers is age population of 0-4 years, frequency of changing diaper and mass of diaper.
• Parameters to be considered for replacement of concrete component by waste materials, especially disposable diapers is density of materials, mass of materials and percentage of replacement. For disposable diapers, the optimal percentage replacement is 5-10% as concrete structure.
• The utilization of disposable diapers as concrete component would be more effective to reduce the waste capacity by be used for constructing road pavement.

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