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Valorization of waste baby diapers in concrete

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A R T I C L E I N F O

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A B S T R A C T

Waste baby diapers constitute a significant part of hygiene waste and currently are primarily landfilled or incinerated. The present study explores the applicability of shredded waste diapers (SWDs) as an innovative viscosity modifying admixture for cement grouts and concrete. A model was proposed which formulates the chemicals that SWDs add to concrete. The model was combined with the building and environmental standards to present the legal framework about using SWDs in different types of concrete. Cement grouts and self-consolidating concrete were designed to validate the viscosity modifying properties of SWDs. A Bingham viscosity model and flow tests were used to evaluate the viscosity modifying performance of SWDs. The present results show that the SWDs are a sustainable route to manufacture highly-effective viscosity-modifying admixtures for concrete.

1. Introduction

Waste baby diapers have received much attention in recent years because of high volume and complicated recycling process. Baby diapers are made up of superabsorbent polymers (SAPs), cellulose, and plastic film. Baby diapers accounted for more than 74% of the US$ 7.1 billion global superabsorbent polymers market with a production rate of 2.119 million tons in 2014 (R&R Market Research, 2015). Currently, waste baby diapers account for 2%–7% of municipal solid waste (Arena et al., 2016). Despite their high volume and excellent water absorption, waste baby diapers have been mostly landfilled (Arena et al., 2016) or incinerated (Cordella et al., 2015). In Europe, 68% of waste baby diapers are landfilled and 32% incinerated, while for the USA, the numbers are 80% and 20%, respectively (Weisbrod and Hoof, 2012). Landfilling causes serious environmental problems such as methane emissions, water pollution, land use, and odor (Aguilar-Virgen et al., 2014; Smith et al., 2001). Furthermore, some studies have shown that the biodegradation of baby diapers in landfills is unlikely to happen due to both low biological activity in landfills and the fact that consumers tend to throw waste baby diapers away by wrapping them in plastic (Espinosa-Valdemar et al., 2014, 2011). Therefore, there is an urgent need to introduce new measures to deal with waste baby diapers. It should also be noted that waste baby diapers, as a bio-degradable waste, were subsumed under EU landfill directive 1999/31/EC (The Council of the European Union, 1999), which had requested to reduce bio-degradable waste in 2016 to 35% of its amount in 1995.

A few attempts to valorize waste baby diapers by separating and reusing their valuable components have been reported (Kim and Cho, 2017; Torrijos et al., 2014). US patent 5558745A (Conway et al., 1996) introduced a process that comprises a few steps to wash, bleach, disinfect, divide, and recover streams of plastic and absorbent materials in waste baby diapers. Another similar methodology has recently been developed in the UK to collect superabsorbent hygiene products after sterilizing and recycling waste diapers (Cox et al., 2015). A combination of an autoclave and a sorting machine was also proposed to recycle waste baby diapers (Arena et al., 2016). However, these methods are costly and produce wastewater that adds up necessary sterilization and wastewater treatment to the total cost of the entire system (Girotto et al., 2017; Maamari et al., 2016). Composting is another method to deal with waste baby diapers (Cook et al., 2007; Espinosa-Valdemar et al., 2014, 2011; Espinosa et al., 2003). Although studies show that pathogens can be destroyed in a composting process (Gerba et al., 1995), polymer degradation time is very long (Colón et al., 2013, 2011; Cook et al., 2007; Stegmann et al., 1993). Microbial biodegradation by different polymer-degrading microorganisms (Lucas et al., 2008; Pathak and Navneet, 2017; Shah et al., 2008) and fungus cultivation

Abbreviations: ASTM, American Society for Testing and Materials; EN, European Norm; LP, Limestone powder; PSD, Particle-size distribution; RCC, Roller-compacted concrete; SAP, Superabsorbent polymer; SCC, Self-consolidating concrete; SD, Standard deviation; SP, Superplasticizer; SWD, Shredded waste diaper; VMA, Viscosity modifying admixture

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Nomenclatures

a	hazardous chemical content per diaper, uq/n [μg/g]
d	diaper dosage, percent by weight of cement [%]
G	yield parameter [N mm]
h	the concentration of a hazardous chemical in combined mixing water of a cement composite in the wake of incorporating shredded waste diapers [ppm in water]
H	plastic viscosity parameter [N mm s]
n	weight of a diaper [g]
N	speed of rotation [rps]
q	the concentration of a hazardous chemical in urine [ppm]
T	torque measured on the viscometer [N mm]
w/c	water-cement ratio [g/g]

(Corrêa et al., 2016; Sánchez, 2009; van Kuijk et al., 2015) are other proposed approaches to recycle waste baby diapers. Further details on the recent technologies for treatment and recycling of waste baby diapers are provided in a recent review by (Khoo et al., 2019). Nevertheless, none of these valorization techniques use waste baby diapers as received without further processing.

The SAP market is estimated to be over US$ 9 billion at a volume of 2.892 million tons in 2020 (R&R Market Research, 2015). Such a significant demand and production rate not only highlights the massive volume of resulting waste but also signifies the importance of valorizing waste baby diapers. A successful valorization method for waste baby diapers should be able to effectively address waste diapers' three main characteristics, in terms of high volume, pathogens, and high water-absorption capacity. Concrete is the most widely used human-made material on earth (Statista, 2018; WBCSD, 2009) and relies on water for rheological properties (Aïtcin, 2015). Such prominent market and water-dependent rheological properties can be used to form a hypothesis that concrete could be the up-and-coming candidate for valorizing waste baby diapers as a product to modify the rheological behavior of concrete. The admixtures that are used for this purpose are called viscosity modifying admixtures (VMAs). If waste diapers were valorized as a VMA at the dosage of 1% of cement content in just 1% of the concrete manufactured worldwide (annual global production 25 billion tons (Statista, 2018)), several hundred thousand tons of waste diapers would be recycled annually. Most importantly, concrete has a highly alkaline environment with a pH of around 13 (Behnood et al., 2016) that kills bacteria, viruses, and pathogens (Eriksen et al., 1996; Farrell et al., 1974; Pancorbo et al., 1988; Randall et al., 2016), making this hypothesis more applicable.

This study hypothesizes that implementing waste baby diapers, wetted by urine, in cement composites would introduce a straightforward route to valorize them as sustainable VMAs. VMAs have a variety of applications in the concrete industry. They can be used in self-consolidating concrete (SCC) to reduce the risk of segregation and bleeding (ACI Committee 237, 2007). They have been used in underwater concrete to reduce washout (Khayat, 1996). They can also be used as pumping aids in shotcreting (Leemann and Winnefeld, 2007). Some studies show that VMAs can help concrete to maintain passing ability and stability at lower levels of cementitious materials (ACI Committee 212, 2016). VMAs have also been used in various types of cement composites such as lightweight expanded polystyrene (EPS) concrete (Li et al., 2018), 3D printing concrete (Chen et al., 2018), shotcretes (Jensen, 2008), and oil well concrete (Sun et al., 2017). Unfortunately, currently-available VMAs are mostly costly, which increases the overall concrete production cost. Hence, introducing new routes to obtain cheaper VMAs is of crucial importance.

To the best of the authors' knowledge, because of the hazardous compounds inside urine, which deteriorate concrete, there has been no study on the application of shredded waste diapers (SWDs) in concrete. Urine has urea (Putnam, 1971), which is an organic compound that potentially affects hydration (Kim, 2017). It also contains chloride (Putnam, 1971), which at high dosages destroys the passivity of concrete (Neville and Brooks, 2010) and speeds up the corrosion of steel rebars (Poulsen and Mejlbro, 2006). That is why both EN 1008 (BSI Committee B/517/1, 2002) and ASTM C 1602 (ASTM Subcommittee C09.40, 2012) specify limits for the chloride ion concentration in combined mixing water of different concrete types. Besides, urine incorporates sulfates (Putnam, 1971) that theoretically lead to different types of sulfate attack in concrete (ACI Committee 201, 2017; Skalny et al., 2002; Taylor, 1997). Accordingly, both EN 1008 (BSI Committee B/517/1, 2002) and ASTM C 1602 (ASTM Subcommittee C09.40, 2012) require limiting this chemical in combined mixing water of concrete as well. The destructive action of these harmful substances depends on the applied dosage of the waste diaper in concrete, and there may exist dosages at which the concentration is lower than the destruction threshold. However, these applicable dosages remain unreported.

The current study aims at filling this scientific gap by a systematic study that begins with presenting a computational model. The model quantifies the concentration of chemicals in combined mixing water of a cement composite following the incorporation of shredded waste diapers (SWDs). Next, it applies the model and compares the average concentration of harmful chemicals to concrete in combined mixing water with the requirements of the relevant standards. Subsequently, this study not only confirms the applicability of SWDs but also provides a legal framework to obtain permitted dosages in different types of concrete. Then, it uses the framework and chooses two SWD dosages to validate the idea of using SWDs as a VMA in cement composites. A Bingham viscosity model and flow tests are applied to evaluate the viscosity-modifying properties of the SWDs.

2. Materials and methods

2.1. Materials

The current investigation involved shredded waste diaper (SWD) manufacture and application as a VMA in cement grouts and self-consolidating concrete. An artificial waste baby diaper was produced by adding an aqueous solution of sodium chloride to fresh diapers. Sodium chloride was used according to both European Disposable and Nonwovens Association (EDANA) and International Organization for Standardization (ISO) test methods which use saline as the test medium for characterizing free swell capacity, fluid retention, and fluid absorption under pressure in diaper ingredients to be used as urine absorbing aids for incontinence (EDANA, 2015a, 2015b, 2015c; Technical Committee ISO/TC 173/SC 3, 2001a,b,c). The concentration of salt (NaCl) was three weight percent of ambient dry diapers. Then, in order to reduce the size of dried artificial waste baby diapers, various types of comminution techniques were investigated. As baby diapers are soft, conventional crushers or grinders could not be employed, and the other comminution methods involving knives and rotors seemed to be more suitable. Finally, a Fritsch Pulverisette 15 cutting mill was utilized for SWD manufacturing. It was able to shred waste baby diapers based on the cutting principle of scissors in which the rotation and airflow do not let the baby diapers settle anywhere. The resulting SWDs are shown in Fig. 1. The fibrous morphology of shredded waste diapers under an optical microscope is exhibited in Fig. 2.

The cement CEM I 52.5 R, provided by ENCI (the Netherlands), was utilized to study the effect of SWDs on the rheological and mechanical properties of cement grouts. The CEM I 52.5 R is an ordinary Portland cement with Blaine specific surface area of ca. 527 m^2/kg. It gains most of its compressive strength after one day (ENCI, 2017), which makes it suitable for grouting or shotcreting applications.

Fig. 1. Shredded artificial waste diapers produced for experimental investigations.

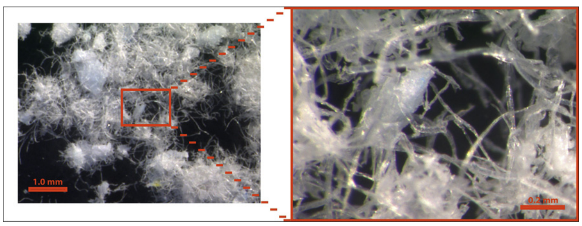

Fig. 2. Morphology of shredded waste diapers under an optical microscope.

The cement CEM III/A 52.5 N, provided by ENCI (the Netherlands), was applied to investigate the influence of SWDs on the flowability and compressive strength of SCCs. The CEM III/A 52.5 N is a binary blend of Portland cement clinker and blast furnace slag that develops strength more smoothly within the first 28 days after casting (ENCI, 2006). It produces less hydration heat and is considered as a sustainable choice for producing mass self-consolidating concrete (SCC).

A polycarboxylic ether-based superplasticizer (SP) with solid content of 35% was used to adjust the flow properties of cement grouts and SCCs. The dosage of the SP refers to the solid as a percentage of the weight of cement. Limestone powder (LP), two types of sand (0–2 mm and 0–4 mm), and two types of gravel (4–8 mm and 8–16 mm) with specific gravities of 2.71, 2.65, and 2.63, respectively, were used in proportioning the self-consolidating concrete. The particle size distribution (PSD) of the powders was measured employing a Malvern Mastersizer 2000 while sieve analysis was used to measure the PSD of the aggregates.

2.2. Methodology

2.2.1. Applicability study

Before performing an experimental program to evaluate viscosity modifying capability of SWDs, the applicability of SWDs in cement composites was studied. The applicability study involved four steps: (1) Presenting a computational model; (2) introducing the legal framework; (3) comparing the results of step 1 and step 2; (4) choosing two dosages to perform experiments. The description of the steps is as follows.

First, a computational model was introduced that formulates the concentration of chemicals in combined mixing water of cement composites in the wake of incorporating shredded waste diapers. An average diaper weight of 41 g (EDANA, 2008) and an average urine output of 161 g (Colón et al., 2011) were used in the computations. The average concentration of hazardous chemicals in urine was extracted from (Putnam, 1971).

Next, the European and the American standards (EN 1008 (BSI Committee B/517/1, 2002) and ASTM C 1602 (ASTM Subcommittee C09.40, 2012)) were utilized to report the requirements about the maximum allowable concentration of chemicals in combined mixing water of different types of concrete.

Then, the average concentrations of hazardous substances, computed in the first step, were compared with the requirements of the relevant standards of the second step to acquire the legal framework about the permitted dosages of SWD in different types of concrete.

Finally, two dosages within the legal framework of almost all concrete types were picked to assess the performance of SWDs as a VMA.

2.2.2. Fresh and hardened properties of cement grouts

Three cement grouts with the water to cement ratio of 0.35 were prepared. Neat cement grout, proportioned without SWDs, was used as the reference. The cement grouts with SWD dosages of 0.5% and 1% by weight of cement were prepared to compare their fresh and hardened properties with those of the reference. These dosages were selected based on the applicability study, elucidated in Sections 2.2.1 and 3.1 of this paper.

The mixtures were prepared using a high shear mixing protocol beginning with mixing SWDs and cement in the dry state at 800 rpm for 90 s at 25 °C. Next, almost 75% of water was added to the mixture and mixed at 2000 rpm for 1 min. Then, the mixer was stopped and scraped for 30 s. Subsequently, the remaining part of the solution of water and SP was added to the mixture and mixed at 2000 rpm for 1 min. Eight

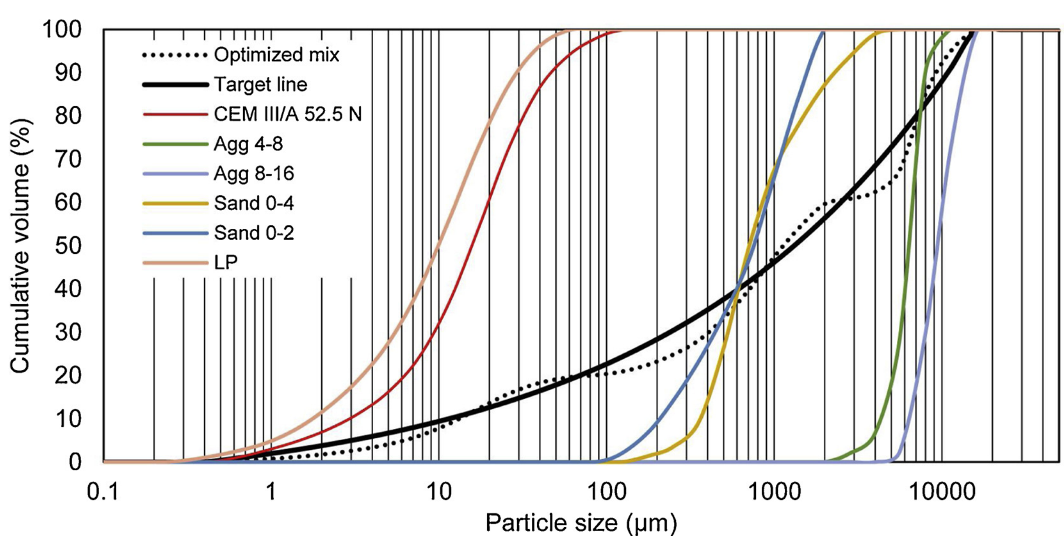

Fig. 3. Particle-size distribution of different ingredients of the self-consolidating concrete. The target line was computed by the modified Andreasen and Andersen model at the distribution modulus of 0.25. The optimized mix is the best fit of the ingredients for the target line.

minutes succeeding the cement and water contact, the mixtures were placed in a Schleibinger Viskomat XL viscometer, equipped with a fishbone-shaped probe, at 25 °C to study the rheological behavior.

A speed sweep protocol was performed that consisted of five one-minute steps of 10, 20, 40, 60, and 80 rpm. The torques reached a quasi-steady state at the end of each speed and were recorded. A procedure similar to (Banfill, 1991, 1990) was used to determine flow parameters, using the Bingham equation

$$T = G + HN \quad \text{(I)}$$

where T is the torque measured on the viscometer [N mm]; N is the speed of rotation [rps]; G is the yield parameter [N mm], and H is the plastic viscosity parameter [N mm s].

Finally, the cement grouts were cast into twelve plastic prism molds, $40 \times 40 \times 160\ mm^3$, and compacted on a vibration table. A plastic film was used to cover the samples and prevent moisture loss from the molds. All the samples were demolded approximately 24 h after casting and then submerged in water at about 20 °C for curing. The compressive strength tests were performed, according to EN 196-1 (BSI Committee B/516/12, 2016), at the curing ages of 1, 3, 7, and 28 days, respectively.

2.2.3. Fresh and hardened properties of self-consolidating concrete (SCC)

The modified Andreasen and Andersen model was used to design SCCs (Brouwers and Radix, 2005; Hüsken and Brouwers, 2008). The particle-size distribution (PSD) of the solid ingredients of the SCCs is illustrated in Fig. 3. A distribution modulus of 0.25 was used in the computation.

Fig. 4 lists the recipes of three self-consolidating concretes. The SCC, having no SWDs, was used as the reference. SWDs were incorporated at the dosages of 0.5% and 1% by mass of cement into the two other mixtures. As mentioned earlier, these dosages were selected based on the applicability study, elucidated in Sections 2.2.1 and 3.1 of this study. The other ingredients were kept the same in all three mixtures.

A standard pan mixer with planetary motion blades was used for the SCC production. SCCs usually demand higher mixing time than normal concrete (Chopin et al., 2004). Therefore, in order to take the effect of powder content, water-powder ratio, and particle size distribution (PSD) of SCCs (Chopin et al., 2004; Larrard, 1999) on the mixing time of the SCC into account, the following procedure was followed. First, all powder ingredients, sand, and SWDs were blended in a dry state for one minute. Then, about 75% of the mixing water was added while further mixing for 90 s. Afterward, a solution of the superplasticizer and the remaining water was added and mixed for one minute. Finally, the coarse aggregates were added and mixed for another two minutes. Previous studies show that the mixing sequence of superplasticizer with the mixture is an important factor in the flowability of cement composites (Ouyang et al., 2016). Superplasticizer was added at the end of the mixing sequence in order to prevent possible competing of superplasticizer molecules with calcium sulfate present in the cement to combine with C_3A and keep all the superplasticizer molecules ready to make concrete more flowable (Aitcin, 1998).

Slump flow, v-funnel, and flow time (T_{500}) tests were used to analyze the fresh properties of SCCs according to EN 12350-8 (BSI Committee B/517/1, 2010a) and EN 12350-9 (BSI Committee B/517/1, 2010b). After mixing, SCCs were cast into six cube molds ($150 \times 150 \times 150\ mm^3$) and covered by a plastic film to prevent moisture loss. All the samples were demolded approximately 24 h after casting and then submerged in water at about 20 °C for curing. The compressive strength tests were performed after 7 and 28 curing days, according to EN 12390-3 (BSI Committee B/517/1, 2009).

3. Results

3.1. Applicability of waste baby diapers in cement composites

In order to determine the applicability of waste baby diapers in cement composites, the average increased concentration of chemicals in the wake of incorporating SWDs should be formulated. The theoretical basis for this formulation is as follows. Consider a baby diaper with the dry weight n is wetted by urine having the volume u containing a hazardous chemical at the concentration q. The hazardous chemical content a shown as the weight of the chemical substance to the weight of a dried diaper is

$$a = uq/n \quad \text{(II)}$$

where:

a = hazardous chemical content per diaper, μg/g;
u = urine output per diaper, ml;
q = concentration of a hazardous chemical in urine, mg/1;
n = weight of a diaper, g.

Assume that the urine-wetted diaper is dried, shredded, and added at the dosage d, percent by weight of cement, to a cement composite having a water-cement ratio w/c. The increased content of the detrimental chemicals in combined mixing water can be formulated as follows

$$h = a\left(\frac{d}{100}\right)\left(\frac{w}{c}\right)^{-1} = \left(\frac{uqd}{100n}\right)\left(\frac{w}{c}\right)^{-1} \quad \text{(III)}$$

where:

h = the concentration of a hazardous chemical in combined mixing water of a cement composite in the wake of incorporating shredded waste diapers, ppm in water;
d = diaper dosage, percent by weight of cement, %;
w/c = water-to-cement ratio, g/g;
u, q, and n as used previously.

In order to utilize Formula III to illustrate the applicability of shredded waste diapers, it is convenient to employ it to create contour plots of the average concentration of hazardous chemicals in combined mixing water, h_{avg}, as a function of d and w/c. The legal framework of application is then presented as various sets of d and w/c, residing in an area confined by the isolines (i.e., lines of constant value) obtained from relevant standards. An average diaper weight of 41 g (EDANA, 2008) and an average urine output of 161 g (Colón et al., 2011) are used in the computations. The average concentration of hazardous chemicals in urine is extracted from (Putnam, 1971).

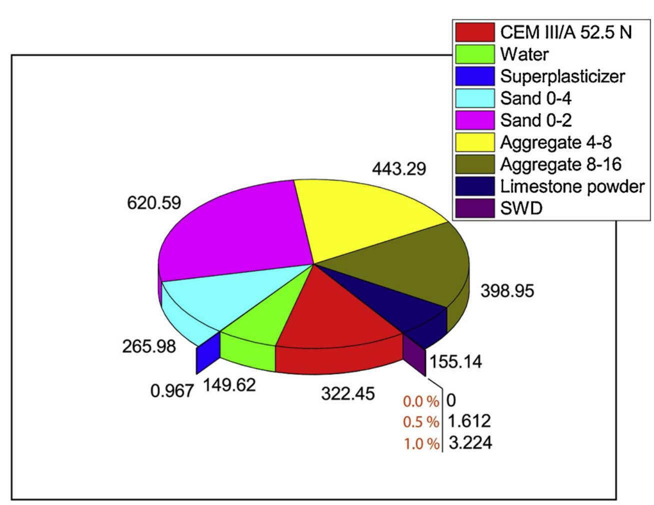

Fig. 4. Recipe of self-consolidating concretes (SCC) incorporating SWDs (kg/m^3). SWDs were used at 0.5% and 1% of cement content. The SCC without SWD was used as the reference.

Fig. 5 presents the contour plot of h_{avg} for chloride, in ppm, by color gradients and isolines for diaper dosages, up to 5% in cement composites with water-cement ratios w/c, between 0.2 and 0.6. The w/c is represented on the horizontal axis and d on the vertical axis. The average chloride content rises exponentially by lowering the water-cement ratio while it peaks up linearly when increasing the diaper dosage.

Fig. 6 illustrates the requirements about the maximum allowable chloride concentration, as Cl^-, in combined mixing water of different concrete types, according to the EN 1008 (BSI Committee B/517/1, 2002) and the ASTM C 1602 (ASTM Subcommittee C09.40, 2012). Both standards limit the maximum concentration of chloride in prestressed and reinforced concrete to 500 ppm and 1000 ppm in water, respectively. However, EN 1008 requires to maintain chloride level below 4500 ppm in non-reinforced concrete, while the ASTM C 1602 has no requirement in this regard.

Replacing the isolines of Fig. 5 with the requirements of Fig. 6 leads to Fig. 7, which presents the legal framework of waste diaper application in concrete concerning chloride concentration. For example, waste diaper dosages of up to 4% at water-cement ratios of higher than 0.25 may fulfill the requirements of the EN 1008 for chloride content in non-reinforced concrete. On the other hand, while diaper dosage of 3% at w/c of 0.6 may justify the requirements for reinforced concrete, the dosage should be lowered to around 1.5% at w/c of 0.3. It is also worth noting that the isolines of Fig. 5 represent the average content of chloride inside a concrete and are well below the legal limits established by the soil quality decree for making unmolded building materials (The State Secretary for Housing Planning and the Environment, 2007).

Fig. 8 demonstrates the contour plot of h_{avg} for sulfate, in ppm, by color gradients and isolines for diaper dosages d, up to 5% in cement composites with water-cement ratio w/c, between 0.2 and 0.6. The maximum limits for the concentration of sulfate in concrete are summarized in Fig. 9. The EN 1008 limits the maximum concentration of sulfate in combined mixing water to 2000 ppm, while the ASTM C 1602 specifies 3000 ppm as compulsory.

In consequence, while diaper dosages of up to 5% at water-cement ratios as low as 0.2 are still within the ASTM C 1602 limits, the diaper dosage may be lowered to 3.5% at similar w/c to comply with the EN 1008. Figs. 8 and 9 can also be used to present the legal framework of waste diaper application in concrete concerning sulfate concentration, as used previously in Fig. 7. It is also worth highlighting that these quantities are far lower than the allowable limits of the soil quality decree for making unmolded building materials (The State Secretary for Housing Planning and the Environment, 2007).

Urine is a dilute solution of other organic and inorganic compounds, as well (Putnam, 1971). Formula III can be likewise used to compute their average concentration in the wake of waste diaper incorporation into cement composites. However, as their concentrations are either negligible or non-effective on concrete, they are not studied here. For instance, the h_{avg} of calcium at $w/c = 0.4$ and $d = 1\%$ is as low as 21 ppm.

3.2. Fresh and hardened properties of cement grouts

As outlined in the Introduction section, cement grouts were one of the two cement composites employed in this study to confirm the viscosity modifying properties of SWDs. Fig. 10 compares and contrasts data on the differences in the rheological properties of cement grouts incorporating SWDs. Bingham flow parameters, namely the yield parameter and the Bingham viscosity parameter are shown on the primary and secondary y-axis, respectively. In general, adding SWDs enhances both the yield and viscosity parameters. More specifically, the rise in the viscosity is significantly higher than that in the yield parameter. For instance, while the viscosity parameter is just under the yield parameter in the reference grout, the value of viscosity rises to more than 2.55 and 2.75 times the yield parameter when adding 0.5% and 1% SWD to cement grouts, respectively.

Fig. 11 compares and contrasts data on the average compressive strength of cement pastes incorporating SWDs. Error bars show the standard deviation (SD). In general, adding SWDs slightly decreases the average compressive strength of cement grouts. More specifically, the mean compressive strength of the cement grout with 1% SWD is approximately 12% less than that of the reference at all ages. As the main constituent of diapers is superabsorbent polymer (SAP), the slight decrease in the compressive strength of grouts incorporating SWDs may be attributed to the presence of SAPs in the matrix. These results are consistent with that obtained in the previous studies on the application of SAPs in cement composites reporting a reduction of the early-age and later-age strength of cement pastes by 20% and 10% by adding SAPs, respectively (Lura et al., 2006). This trend can be attributed to the fact that the SAP gels are initially filled with water, but as hydration goes on, cement particles absorb the water inside SAP gels, leaving a porous structure similar to that in cement composites having air-entraining agents (Laustsen et al., 2015; Riyazi et al., 2017).

3.3. Fresh and hardened properties of self-consolidating concretes (SCCs)

As mentioned previously, in addition to cement grouts, SCCs were utilized to assess the viscosity-modifying performance of SWDs. Fig. 12 illustrates the effect of SWDs on three rheological parameters of SCCs, namely flow diameter, V-funnel time, and T_{500} time. In all cases, adding SWDs increases the flow time (V-funnel or T_{500}) and decreases the spread (flow diameter) of the SCCs.

More specifically, as can be seen in Fig. 12, the addition of SWDs modifies the slump flow diameters of SCCs. SCCs are classified into three classes of SF1, SF2, and SF3, based on their slump flow, and each class is suitable for a specific category of applications (EFNARC, 2005). Hence, adding SWDs can be regarded as a sustainable method to change the application of SCCs. Besides, Fig. 12 confirms that SWDs modify both the v-funnel time and T_{500} of SCCs. Both of these tests are used to appraise the filling ability (ACI Committee 238, 2007) and assess the viscosity of SCCs indirectly (EFNARC, 2005). The adjustments in the viscosity and the yield stress of SCCs are in agreement with the rheological properties of cement grouts shown in Fig. 3 and confirm a viscosity modifying effect, validating the applicability of SWDs as viscosity modifying admixture for self-consolidating concretes.

The average compressive strength of self-consolidating concretes

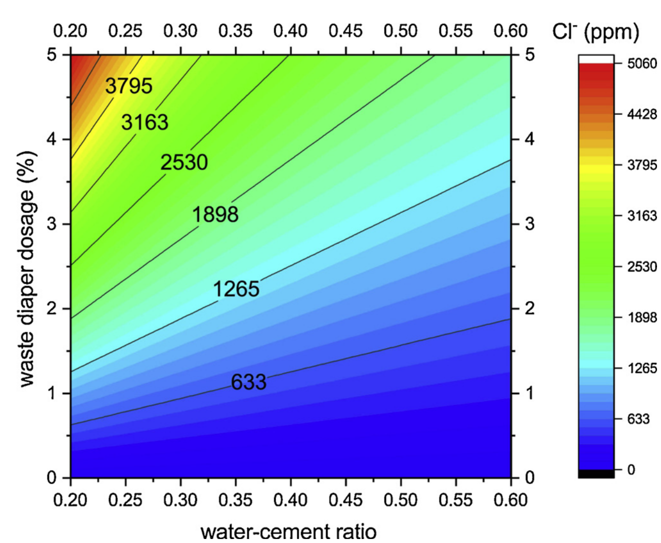

Fig. 5. Average concentration of chloride as Cl^- in combined mixing water in the wake of incorporating shredded waste diapers into a cement composite. Formula III was used in the computation.

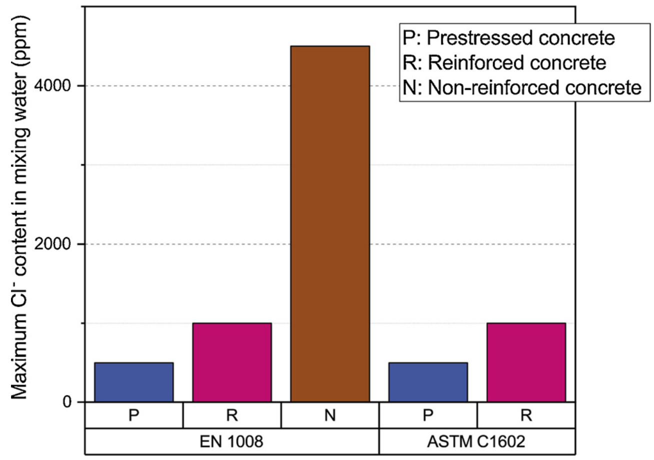

Fig. 6. Maximum limits for the concentration of chloride as Cl^- in combined mixing water of three types of concrete, namely prestressed concrete, reinforced concrete, and non-reinforced concrete, according to EN 1008 and ASTM C1602 (ASTM Subcommittee C09.40, 2012; BSI Committee B/517/1, 2002).

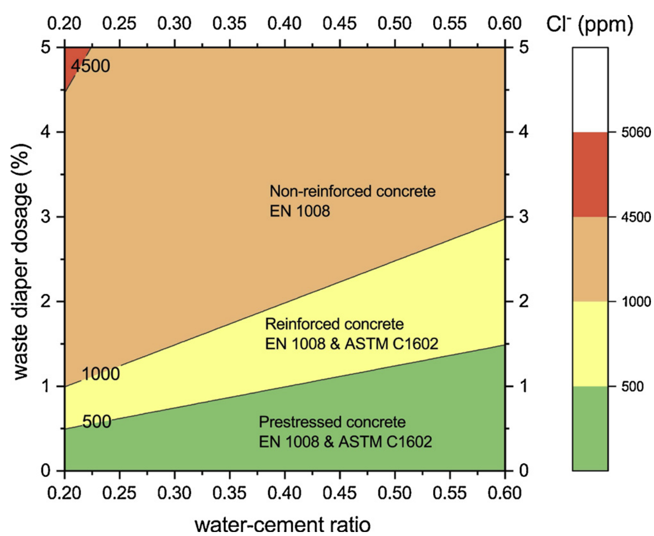

Fig. 7. Legal framework of waste diaper application in concrete concerning chloride concentration.

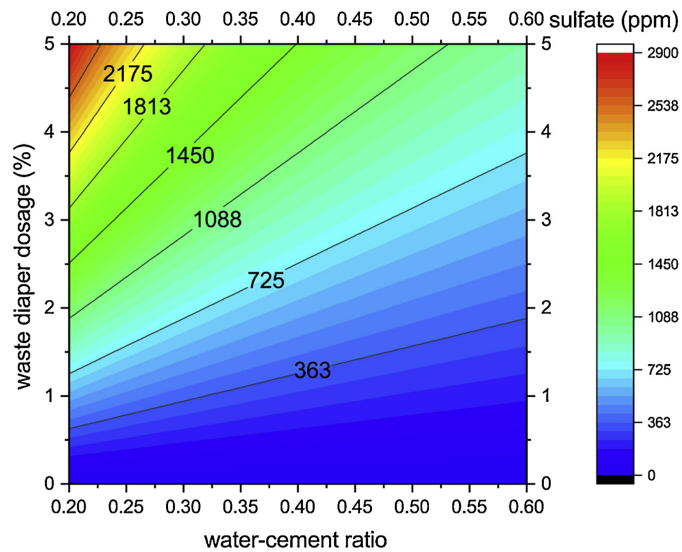

Fig. 8. Average concentration of sulfate in combined mixing water in the wake of incorporating shredded waste diapers into a cement composite. Formula III was used in the computation.

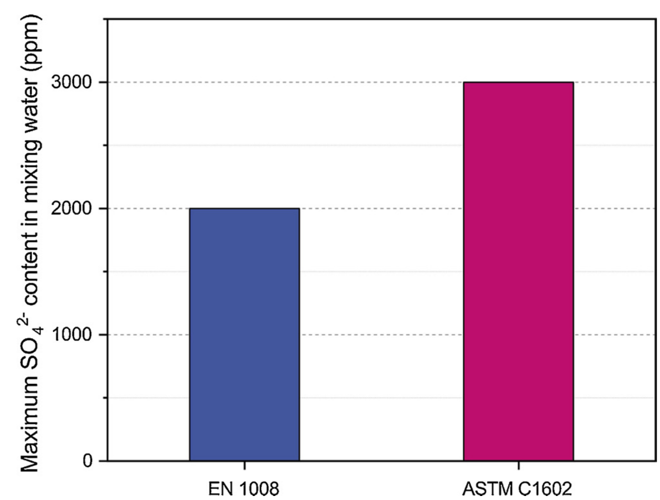

Fig. 9. Maximum limits for the concentration of sulfate, as SO_4, in combined mixing water of concrete, according to EN 1008 and ASTM C1602 (ASTM Subcommittee C09.40, 2012; BSI Committee B/517/1, 2002).

(SCCs) proportioned with SWDs at 7 and 28 days is shown in Fig. 13. The error bars show the standard deviation (SD). The results show that SWDs do not influence the compressive strength of SCCs at the dosages used in this study. This effect may be attributed to the two contradicting influences of SAPs inside the SWDs. On the one hand, they absorb the free water inside SCCs, provide internal curing, and reduce the relative water to cement ratio, leading to a higher value of compressive strength. On the other hand, they produce small water reservoirs that are converted to small cavities inside the matrix after hydration, resulting in a lower value of strength (Assmann, 2013).

4. Discussion

The results indicate that shredded waste diapers (SWDs) modify the rheological properties of cement pastes and self-consolidating concrete. The category of additives that increase yield stress value, plastic viscosity and apparent viscosity of cement composites are referred to as viscosity modifying admixtures (VMAs) (Palacios and Flatt, 2015), viscosity enhancing admixtures (VEAs) (Khayat and Mikanovic, 2011), or rheology modifiers (Braun and Rosen, 2000).

The main challenge in recycling and valorization of waste baby diapers is the cost of the process. From an economical point of view, a

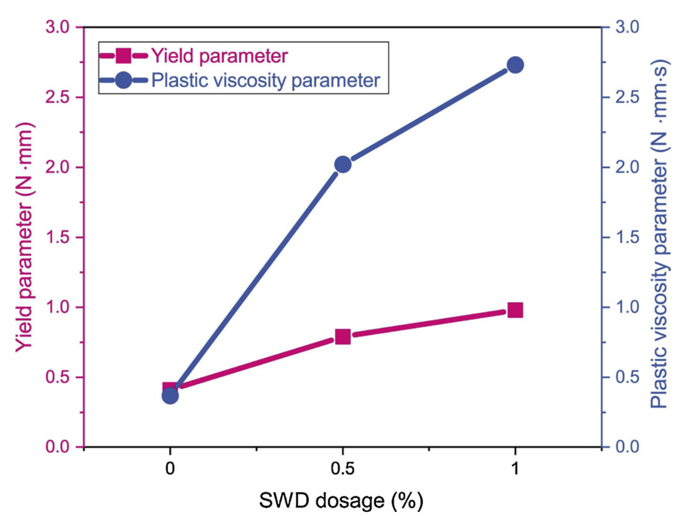

Fig. 10. Influence of SWDs on the rheological properties of cement grouts.

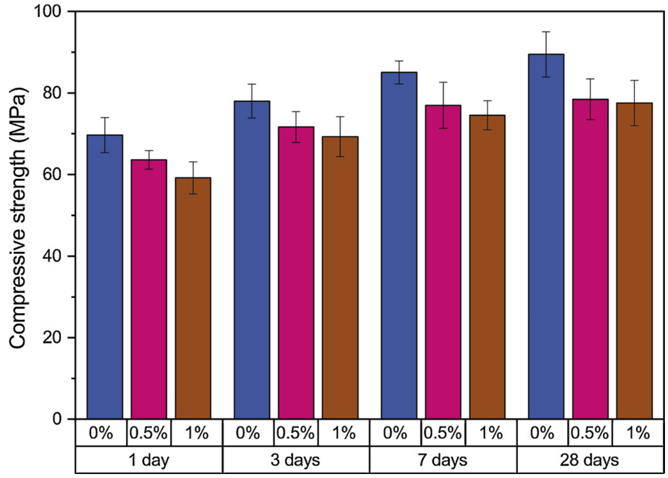

Fig. 11. Influence of SWD content on the average compressive strength of cement grouts. Error bars show the standard deviation.

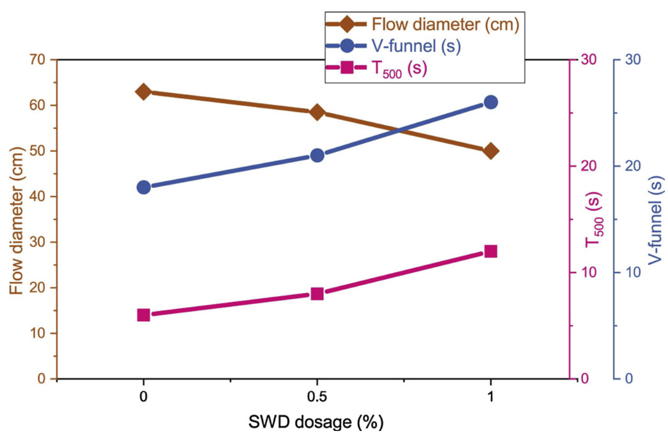

Fig. 12. Effect of SWD on the flow parameters of SCC.

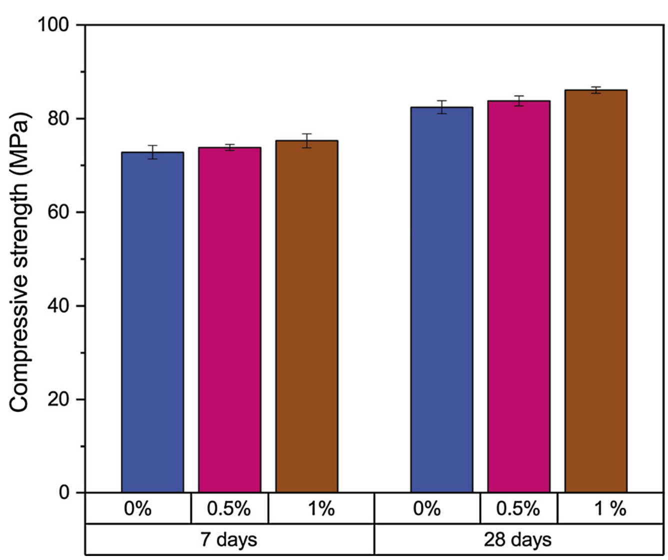

Fig. 13. Influence of SWD dosage on the average compressive strength of SCCs. Error bars show the standard deviation.

recycling process usually consists of five steps: (1) collection; (2) shredding; (3) sterilization; (4) sophisticated separation technology; (5) secondary waste treatment. Valorization of the shredded waste diapers in concrete only involves the first two steps of collection and shredding and eliminates the need for the other three more expensive steps, resulting in higher added value. On the other hand, the technological gap between developing and developed countries has resulted in the implementation of recycling technologies only in developed countries (Khoo et al., 2019). Developing countries only rely on landfilling or incineration for waste diaper disposal. The higher added value can be used to create jobs in developing societies in sectors related to the collection and shredding of diapers for valorization in concrete. From an environmental point of view, waste baby diapers require over half a millennium for full degradation in landfills, and incineration would produce hazardous ashes containing heavy metals and dioxin (Khoo et al., 2019; Sun et al., 2016). Valorization of SWDs in concrete may alleviate these environmental problems.

The main ingredients of concrete are water, binder (e.g., Portland cement), and filler (i.e. aggregates). A large number of waste materials that contain large quantities of silicon and calcium have already been valorized as supplementary cementitious materials (SCMs) in concrete (Aprianti, 2017; Federico and Chidiac, 2009). These include industrial by-products and wastes (e.g., silica fume, fly ash, waste glass, and slag) and agricultural waste (e.g., wood waste ash, bagasse ash, bamboo leaf ash, rice husk ash, and corn cob ash) and water treatment sludge (De Carvalho Gomes et al., 2019). Besides, a vast number of materials that have reasonable strength or can be used to make aggregates and are stable in cement environments such as plastic waste (Saikia and de Brito, 2012), dimensional stone waste (Rana et al., 2016), steel slag (Grubeša et al., 2016), and water treatment sludge (De Carvalho Gomes et al., 2019) have already been valorized as aggregates in concrete. Valorization of waste diaper in concrete differs from these waste valorization methods in that it does not target binder and filler, but it aims at the available water for mixing inside concrete. Baby diapers consist of SAPs, fluff pulp, and nonwoven fabric. As SAPs are the main absorbing constituent of baby diapers and the main driver of the 44% baby diaper weight reduction in recent years (EDANA, 2015d), the working mechanism of a diaper is mainly dominated by the swelling action of SAPs inside SWDs. SAPs can absorb and retain water under pressure, resulting in a higher concentration of a suspension and higher value of viscosity.

Fig. 14 illustrates the morphology of the macropores developed by SWDs inside polished samples of hardened cement grouts, performed by an FEI quanta 600 environmental scanning electron microscope (ESEM). Micrographs were recorded by both secondary and backscattering electron detectors (MIX mode) at 5 kV with a spot of 3.0. During the mixing, superabsorbent polymers inside SWDs absorb water and swell. After setting, the swelling of SWDs results in local macropores containing water inside hardened cement grouts that provide internal water reservoirs for cement hydration. Later, these water reservoirs are dried and form small cavities inside the matrix after hydration.

In order to assess the possible influence of the SWDs in the pore structure of the cement grouts, mercury intrusion porosimetry (MIP) was performed. Fig. 15 presents the pore size distribution of cement grouts containing different dosages of SWDs, performed by an AutoPore IV mercury porosimeter. The samples had a particle size of 2–4 mm. Before testing, samples were dried in the oven at 60 °C for 48 h. The tests were performed at the pressure range of 0.7 mPa to 227.5 MPa. The contact angle and surface tension of mercury were 130° and 485 mN/m, respectively. The graph confirms that the influence of SWD on porosity of the matrix is local and it does not influence the pore structure of the surrounding matrix significantly.

The applicability study in Section 3.1, presents a computational model and applies it to formulate the average content of destructive ions in cement composites with different water-cement ratios and diaper dosages. In view of the fact that the main focus of this research is the change in the rheological behavior of cement composites thanks to the water uptake by baby diapers, SWDs are used at the maximum dosage of 1% of cement weight. This dosage is appropriate for

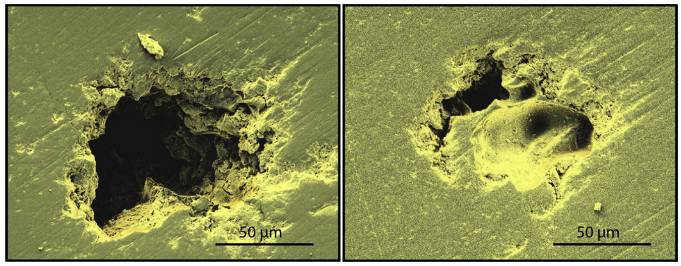

Fig. 14. Morphology of the macropores developed by SWDs inside hardened cement grouts.

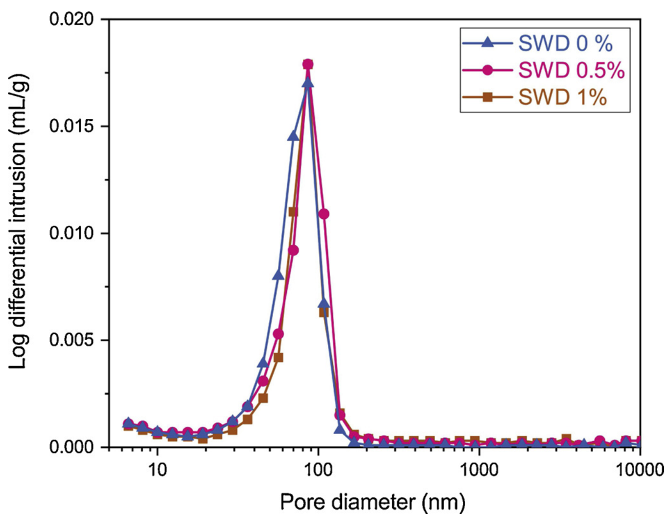

Fig. 15. Pore size distribution of cement grouts containing different dosages of SWD, measured by MIP.

reinforced concrete. On the other hand, the applicability study paves the way to apply SWDs at higher dosages by presenting appropriate dosages in the other types of concrete. Given the fact that SAPs, which are the main absorbing constituent of SWDs, have been employed to manufacture air-entrained concrete (Riyazi et al., 2017), frost-resistant concrete (Laustsen et al., 2015), or fire-resistant concrete (Asako et al., 2004), further work may be performed to develop new types of concrete with SWDs.

The computational model only considers diapers wetted by urine and does not include diapers containing feces. Furthermore, urine contains bacteria, viruses, and pathogens. These harmful microorganisms may be one of the main concerns about incorporating SWDs into cement composites. Although studies showed that the high pH of cement composites kills dangerous microbes (Eriksen et al., 1996; Farrell et al., 1974; Pancorbo et al., 1988; Randall et al., 2016), further research may include urine in SWDs to assess the level of disinfection.

5. Conclusions

This paper introduces an innovative mindset towards waste baby diapers. They are not only not detrimental to cement composites but also useful in terms of modifying the viscosity of cement grout and concrete. The article develops a systematic study by proposing a computational model, applying the model, and validating the idea by two cement composite systems. Based on the obtained results, the following conclusions have been reached:

- A model is proposed that computes the average concentration of chemicals in combined mixing water of a cement composite in the wake of incorporating shredded waste diaper. The model is combined with the relevant standards to present a legal framework about the applicability of waste diapers in different types of concrete.
- The appropriate dosages of the waste diaper in concrete depend on the type of concrete, water-cement ratio, and the waste diaper dosage. Waste diaper dosages as high as 5% in non-reinforced concrete at water-cement ratios ranging from 0.25 to 0.6 and as high as 2% in reinforced concrete at water-cement ratios ranging from 0.4 to 0.6 can be used.
- Shredded waste diapers (SWDs) modify the rheological behavior of cement grouts and concrete by enhancing the yield stress and viscosity and can be classified as a sustainable source for producing highly effective VMAs in the concrete industry. A maximum SWD dosage of 1% showed an excellent rheological effect on self-consolidating concrete (SCC) with no effect on its compressive strength.
- Shredded waste diapers (SWDs) affect the pore structure locally by producing water reservoirs but do not affect the pore structure of the surrounding matrix significantly.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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