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BRENNO AUGUSTO MARCONDES VERSOLATTO

THE USE OF CONSTRUCTION AND DEMOLITION SOLID WASTES AS A GABION FILLING MATERIAL FOR HYDRAULIC WORKS

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Brenno Augusto Marcondes Versolatto

THE USE OF CONSTRUCTION AND DEMOLITION SOLID WASTES AS A GABION FILLING MATERIAL FOR HYDRAULIC WORKS

O USO DE RESÍDUOS DE CONSTRUÇÃO E DEMOLIÇÃO COMO MATERIAL DE PREENCHIMENTO DE GABIÃO EM OBRAS HIDRÁULICAS

Dissertation presented to the master's degree Program in Smart and Sustainable Cities of University Nove de Julho, as a requirement for Master Degree obtaining.

Advisor: João Alexandre Paschoalin Filho, PhD
Co-Advisor: Andrea Ghermandi, PhD

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By

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____
João Alexandre Paschoalin Filho, Ph.D – University Nove de Julho – UNINOVE

____
Andrea Ghermandi, Ph.D – University of Haifa - Israel – U.HAIFA

____
António José Guerner Dias, Ph.D – University of Porto – Portugal

____
Joana Ribeiro, Ph.D – University of Coimbra - Portugal

____
Wilson Levy, Ph.D – University Nove de Julho – UNINOVE

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“When one door closes, another opens; but we often look so long and so regretfully upon the closed door that we do not see the one which has opened for us.”.

Alexander Graham Bell

ABSTRACT

Due to their low implantation costs and constructive speed, gabions are commonly used for hydraulic channel linings. However, these gabions are filled with natural materials like rocks. In most cases, these gabions are not used for structural purposes, so the use of rocks for filling them is unnecessary and could be substituted by other materials. Civil construction is responsible for generating large amounts of solid wastes. Many authors notice that the construction and demolition wastes can range 50 to 70% urban solid waste total amount generation worldwide. In some situations, these wastes are usually dumped in improper areas, illegal landfills, and riverbanks. The improper management of construction and demolition wastes (C&DW) affects public health and causes the deterioration of urban areas. Many researchers have been studying recycling, and reuse as essential tools for C&DW management in civil construction works. C&DW recycling and reusing generally allow purchasing cost reduction and reduce greenhouse gas emissions. Facing it, this research is focused on the technical study of C&DW using for gabion filling, pointing out this material as a technical solution concerning sustainability aspects. Solid waste reduction techniques are crucial, especially when the environmental impacts caused by buildings constructions are brought to light. To obtain the necessary data for further analysis, laboratory tests were performed to obtain C&DW and natural rock physical and hydraulic characteristics such as durability and water absorption, necessary for gabion designs. In addition, an economic assessment was performed to assess the purchasing costs for the substitution of rocks for C&DW for gabion filling. The obtained data and the performed analysis showed that the studied C&DW sample met the technical standards and can be used as gabion filling material. The economic assessment brought to light the economic advantages and low costs of substituting rocks for C&DW for gabions filling.

Keywords: Recycling, reuse, civil construction, sustainability, solid wastes, gabions.

RESUMO

Os gabiões são amplamente utilizados para revestimento hidráulico de canal devido ao seu baixo custo de implantação e velocidade construtiva. No entanto, esses gabiões são geralmente preenchidos com materiais naturais como rochas. Esses gabiões, na maioria dos casos, não são utilizados para fins estruturais, portanto, a utilização de pedras para fins de enchimento não é estritamente necessária e poderia ser substituída por outros materiais. A construção civil é responsável pela geração de grandes quantidades de resíduos sólidos. Muitos autores relatam que os resíduos de construção e demolição correspondem a 50-70% do volume de todos os resíduos sólidos urbanos gerados todos os dias. Na maioria dos casos, esses resíduos estão sendo despejados em áreas impróprias, aterros ilegais e margens de rios. A gestão inadequada dos resíduos de construção e demolição (RCD) afeta a saúde pública e causa a deterioração das regiões urbanas. Muitos pesquisadores estão estudando a reciclagem como uma ferramenta essencial para a gestão do RCD em obras de construção civil. A reciclagem e reuso do RCD permite reduzir os custos de aquisição de matérias-primas e transporte para aterros sanitários adequados. A reciclagem também reduz as emissões de gases de efeito estufa. Este projeto propõe um estudo técnico do uso do RCD como material de enchimento para gabiões. Esta pesquisa vai identificar a melhor solução para o preenchimento de gabiões com base em considerações de sustentabilidade. O desenvolvimento de técnicas que reduzam a quantidade de resíduos sólidos e seus impactos ambientais é crucial, especialmente considerando os significativos efeitos globais da poluição do setor da construção civil. Foram realizados testes laboratoriais para obter características físicas e hidraulicas de engenharia do RCD e pedra natural, como durabilidade e absorção, necessários para o dimensionamento de gabião. Adicionalmente, uma avaliação econômica foi realizada para se verificar os custos envolvidos na troca de recursos naturais por RCD no preenchimento de gabião. Os resultados obtidos mostraram que o RCD atendeu aos requisitos de normas técnicas e este possui uma viabilidade econômica satisfatória em comparação a pedra natural.

Palavras-chave: Reciclagem, reuso, construção civil, sustentabilidade, resíduos Sólidos, gabiões.

FIGURES LIST

TABLE LIST

SYMBOL LIST

Q Flow;

V Speed;

A Area;

P Wet perimeter,

Rh Hydraulic radius;

B Width;

b Smallest width;

y Water thickness;

n Manning coefficient;

i Declivity;

Mesh sieve;

Ø Diameter.

ABBREVIATIONS LIST

ABRECON	Associação Brasileira para Reciclagem de RCD (Brazilian Association for C&DW Recycling);
C&DW	Construction and demolition waste;
Fck	Feature compression know;
INHAB	Inhabitant;
MSW	Municipal solid waste;
USW	Urban solid waste.

UNIT LIST

mm	Millimeter;
cm	Centimeter;
m	Meter;
t	Tonne;
kg	Kilogram;
g	Gram;
kN	Kilonewton;
MPa	Megapascal;
s	Seconds;
min	Minutes.

SUMMARY

1 INTRODUCTION AND JUSTIFICATIVE

Urban planning plays an essential role in sustainable growth, land use, and occupation. Among the challenges that municipalities must tackle, urban solid waste management can be highlighted.

Coffey and Coad (2010) state that USW management requires significant budgets and, not all cities, especially those localized in low-income countries, do not have enough wealth to perform proper transportation, disposal, and treatment of their USW.

According to Leite, Damasceno, Reis, and Alvim (2018), improper waste management leads to environmental problems. The authors also notice that, in some situations, urban solid wastes are disposed of in non-legal areas like riverbanks, streams, water springs, and natural sites. To Gonzaga, Rocha, Lira, and Silva (2017), the waste management policies, performed improperly, cause diseases spreading and insects' proliferation, becoming a serious public health problem.

Evangelista, Costa, and Zanta (2010) state that urban solid waste generation has been presenting a growing trend, mainly influenced by consumption and population growth. The authors also highlight the high costs of USW transportation and disposal costs. Table 1 presents some data about the USW collected mass in the city of São Paulo, Brazil.

Table 1
Mass values of waste collected in the city of São Paulo.

Year	Urban Waste - São Paulo City (t)						
	Domestic – All kinds of waste	Domestic – Recycling waste	Health waste	Ecopoint – Wood, C&DW, glass, large objects, others.	Street sweeping	Cleaning of surface drainage devices	Total
2010	3,722,061	36,303	No data		102,870	19,811	3,881,045
2011	3,807,029	48,493			96,063	24,490	3,976,075
2012	3,799,544	56,908			133,886	14,581	4,004,919
2013	3,831,455	66,439			118,347	7,955	4,024,196
2014	3,802,244	65,833			113,510	9,517	3,991,104
2015	3,801,404	86,714			106,513	10,050	4,004,681
2016	3,632,342	86,283	41,013	286,961	91,772	12,456	4,150,827
2017	3,682,260	87,921	41,811	366,171	92,969	12,431	4,283,563
2018	3,697,148	76,907	42,131	413,822	77,448	8,929	4,316,385
2019	3,680,045	80,454	42,645	447,736	79,633	17,807	4,348,320

Source: Municipal Authority of Urban Cleaning of São Paulo City (2020).

Worldwide, building construction is responsible for large amounts of USW generation and high consumption of raw materials by their daily activities. To Motta and Aguilar (2009), building construction can address to environmental impacts. Building activities consume 40% of all-natural resources, 40% of electric energy, and 40% of greenhouse gas emissions.

However, despite the severe environmental impacts of building construction, there is still a lack of technical bibliography about management tools developed under sustainability concepts. So, the importance of studies concerning construction and demolition reuse or recycling in construction fields as raw material for alternative construction materials can be highlighted. Vieira and Pereira (2015) stated that the construction and demolition wastes used in construction sites could perform an essential role in reducing the need for natural raw materials; furthermore, it can also reduce construction costs (Arif, Bendi, and Toma-Sabbagh, 2012; Oyedele, Regan, Meding, Ahmed, and Elnokali, 2013; Paschoalin Filho, Bezerra, Oliveira, and Faria, 2017; and Tam, Kotrayothar, and Loo, 2009).

According to Yuan (2017), worldwide, there is not a unique definition for C&DW; each country can address specific regulations and standards about it. However, a common aspect can be pointed; the C&DW´s mass is composed mainly of debris like tiles, bricks, soil, concrete, ceramic materials, etc (Menegaki & Damigos, 2018).

The construction and demolition wastes can reach up to 40% of the total USW daily generated globally (Jin, Yuan, & Chen, 2018). In Brazil, the percentage of C&DW can vary between 40-70% of the total USW mass generated (Brazil, 2005). Huang, Wang, Kua, Geng, Bleiscwitz, and Ren (2018) state that, in China, the C&DW can vary between 30 to 40% of the total mass of USW. The amount and the composition of C&DW can be different in many places. This difference will depend on local economic growth, legislation, public policy, constructor expertise, building construction method, regional planning, and others (Menegaki & Damigos, 2018).

In China, the C&DW are often dumped on improper landfills without any previous segregation. China figures as the country that presents lower recycling rates globally; only 5% of C&DW generated is often recycled or reused (Menegaki & Damigos, 2018). Saez, Merino, Amores, and Gonzales (2011) state that the C&DW recycling rates can reach up to 80% in some European countries, like Denmark, Ireland, Germany, Estonia, and the Netherlands. According to Saez and Osmani (2019), each country of the European Union performs specific C&DW management policies. However, all of these policies must be under the general legislation imposed by the European Union. On the other hand, according to Miranda, Torres, Vogt, Brocardo, and Bartoli (2016), the recycling rates are under 20% in medium-income countries like Brazil.

Blaisi (2019) notices that four steps must support a C&DW policy before it comes into force: (i) awareness of waste management; (ii) waste management regulations and systems; (iii) sustainable building technologies; and (iv) C&DW management plans for construction and demolition works.

There are many technical essays about the C&DW uses for sustainable buildings constructions. Most of these studies describe the manufacturing and the assessment of materials obtained using C&DW (e.g., masonry blocks; bricks; tiles; etc.). However, there is a lack of technical literature about C&DW uses for hydraulic works, such as channels, river coatings, etc.

Many different technical solutions can be used for river coatings. Among these, gabions can be pointed out. Gabions are often composed of a metallic web resistant to chemical attacks and corrosion. The web wires are coated by a layer of polymeric material, increasing their strength and protection. The gabions are often filled with arranged rocks in proper dimensions. Gabions can be assembled in different sizes and types, as like gabion baskets, gabion mattresses, gabion sacks, decorative gabions, etc.

Compared to concrete, the most used material for hydraulic works, gabions need fewer natural resources for their construction, like water, sand, gravel, cement, electricity, wood, etc. However, gabions are filled with rocks. Rock extraction often leads to several environmental impacts, high energy consumption, and greenhouse gas emissions in the quarries. This situation hampers the environmental advantage of gabions compared to concrete use.

Therefore, the research performed (reported in this dissertation) had as guide question the following: "Do the construction and demolition wastes have technical and economic characteristics that enable their use for gabion filling regarding hydraulic construction works?"

To reach the answer to that question, laboratory tests were performed to obtain C&DW technical and physical characteristics. These characteristics were assessed and compared to technical standards and requirements for gabion filling. The economic assessment of C&DW using, rather than rock, was performed framing a real hydraulic construction work, placed in the East Zone of the City of São Paulo. The construction work consists of renewing the coating of Jacu Pessego's River.

This dissertation was guided by the following items:

- **Introduction and Justificative**: The shortage of technical acknowledgment about the research issue is discussed, and a research question is conjured up. The research goals are also shown.
- **Literature Review**: This item brings the come-out literature about the studied issue. This item was written to feed the reader with state of the art about C&DW recycling and reusing. The most recent scientific papers from relevant technical journals were gathered and presented in this item.
- **Materials and Methods:** The performed research procedures are described in this item.
- **Results and Discussions**: The figured-out data are discussed in the light of the theoretical literature. The C&DW characteristics are likened to those gotten for Rock samples. The technical assessment was examined under the Technical Standards requirements. The economic feasibility of C&DW use is also pointed-out.
- **Conclusions**: This item brings the findings and addresses suggestions for ahead research.
- **References**: All the used references are shown in this item.

1.1 RESEARCH GOALS

1.1.1 PRIMARY GOAL

This research's primary goal is to assess C&DW to find its technical and economic feasibility for gabions filling, focusing on their use for hydraulic works.

1.1.2 SPECIFIC GOALS:

The specific goals of this research are presented below:

a) Perform laboratory tests for physical characterization of C&DW and rock samples under saturated and non-saturated conditions;
b) Obtain the degradation conditions due to water flow;
c) Perform economic feasibility assessment of the use of C&DW, instead of natural resources, for gabion filling for hydraulic works.

2 LITERATURE REVIEW

Due to the urban center’s industrial and economic development, the search for natural resources was intensified to supply regional demands, causing changes in the local environment. The mining processes used for raw materials obtaining and the outdated construction methodologies for buildings execution require high amounts of production inputs and produce large volumes of solid wastes.

As cited by Jin, Yuan, and Chen (2018), civil construction activities are responsible for 40 to 60% of all solid waste produced worldwide. Marrero, Puerto, Rivero-Camacho, Freire-Guerrero, and Solís-Guzmán (2017) inform that the civil construction industry is also responsible for pollutant gas emissions. According to the authors, about 97% of these emissions are caused by burning fuels, transportation, machinery use, etc.

To Almeida, Silva, Formiga, Crispim, Medeiros, Paiva, and Silva (2015), the sizeable C&DW generation by the construction works should be linked to outdated building processes performed by the construction companies. The authors also notice that about 98% of construction works still use building methodologies that consume large amounts of inputs and generate critical wastes volumes.

Faniran and Caban (1998) stated that the authors concluded that the project stage is one of the leading causes of waste generation in civil construction. By adopting measures in the project stage, it is possible to minimize the amount of waste generated. In the same line, Ajayi, Oyedele, Kadiri, Akinade, Bilal, Owolabi, and Alaka (2016a) and Ajayi et al. (2016b) show that the project's design stage can be considered one of the most critical steps for the prevention of waste generated in the construction industry. The authors evaluate that during work planning, by mapping the activities and integrating different designs, predicting the generation of construction waste and reducing it is possible. They conclude that it is indispensable to achieve efficient design, resulting in a cultural change of belief in waste inevitability.

According to Camelo (2019), the C&DW is usually dumped on non-occupied areas, near river margins, illegal landfills, and environmental reserves. In neighborhoods characterized by high population density, the unlawful dumping of C&DW is increased by the low population awareness, lack of effective policies, environmental education initiatives absence, poverty, others. The C&DW, when dumped improperly, can severely cause public health problems.

Figure 1(a) shows the illegal disposal along the Jucuruçu river. Figure 1(b) represents some illegal disposal in a landfill, in this case, located in Vitoria da Conquista City.

(a) (b)

Figure 1 Illegal disposal on the river’s margin and landfill.
Source: (a) from Claysson Motta/ Prado Noticia, 2018.
(b) from Anderson BLOG, 2017.

It is possible to recycle and reuse C&DW through proper management tools, reducing the environmental impacts that the civil construction industry has caused. Despite the growing demand for new buildings to meet the uncontrolled growth of cities, the concern of C&DW management is a crucial step to be taken by construction companies to make their activities more sustainable. C&DW recycling and reusing add economic value to a material that would be discharged and give birth to a new market, generating jobs, monetary worth, and social inclusion.

Without adequate urban planning, cities deal with several problems to provide urban and social infrastructure. One of the main problems lies in the occupation or reduction of flood areas during rain periods.

Such locations are natural resources for the amortization of rains and flow regulation in rivers and streams. With their occupation and urban development, rivers become insufficient to collect and route the water volume precipitated in the watershed basin. Thus, floods occur due to the water level's elevation, causing material losses for the population and catalyzing disease vector’s proliferation. In some cases, due to the volume of flood and drag force, erosive processes may occur along the margins and bottom, and general terrain instability may arise due to the ferocity of water passage.

Figure 2 illustrates an area of an advanced erosive process caused by tropical storm "Agatha" in 2010, which caused land instability and put the lives of the citizens and residences at risk. Figure 3, on the other hand, shows a rectified urban stream - Corrego da Ressaca, Belo Horizonte/ Brazil - for the implementation of an urban road. Due to water pollution and low site conservation, the stream needed a readjustment of the channel section and a new cladding for the margins and bottom with better resistance to pollutant attacks.

Figure 2. The erosive process caused by tropical storm "Agatha."
Source: Maccaferri, 2016.

(a) Before (b) After

Figure 3. Channel rectification in an urban center.
Source: Maccaferri, 2012.

2.1 CONSTRUCTION AND DEMOLITION WASTE GENERATION

As noticed by Wang, Wu, Tam, and Zuo (2019), it has been estimated that more than 10 billion tonnes of C&DW were generated in the world in 2017. In 2016 the European Union generated 923,540,000 tonnes of C&DW (Eurostat, 2017); this amount is more considerable than the C&DW generation in 2014 when it was estimated to produce 860 million tonnes (Eurostat, 2014).

In the USA, in 2014, approximately 540 million tonnes were produced (28.9 million tonnes by construction activities and 505.1 million by demolition services). Australia and China in 2014 had 19.5 million tonnes and 1.13 billion tonnes, respectively (Menegaki & Damigos, 2018). The United Kingdom, in 2012, generated 200 million tonnes of waste, of which the civil construction industry produced 50 %. Blaisi (2019) informs that in Saudi Arabia, in 2016, a total of 131,436 tonnes of C&DW was generated, and, comparing 2016 to 2017, the author has reported an increase of about 10%.

According to ABRECON (2017 as cited in Camelo, 2019, p. 29), citizens generate an average of 500kg/year of C&DW in Brazil, representing 60% of all municipal solid waste generation. In their opinion, about 70% of the C&DW could be reused and recycled, generating jobs and improving the economy. Chistófori, Oliveira, and Emreick (2017) show that in medium to large Brazilian cities, the generation of C&DW can vary between 400 and 700kg/ inhab./ year.

Tables 2 and 3 show some estimated waste generation values magnitudes for some national and international locations. According to the authors Camelo (2019), Carneiro, Cassa, Quadros, Costa, Sampaio, and Alberte (2000), Da Silva and Giacchini (2017), the composition of C&DW may vary by location, see Table 4.

Table 2
Estimated generation of international C&DW.

Source	Country	Year	Total C&DW (t/day)	*Per capita* rate (kg/inhab/year)
Zhen (2017)	Spain	2012	90.4	69
	Italy	2012	136.9	80
	Germany	2012	268.5	122
Asgari (2017)	Teerã/Iran	2016	3.81	155
Zhen (2017)	Belgium	2012	68.49	179
Ram e Kalidindi (2017)	Chennai / Índia	2013	3.12	245
Zhen (2017)	France	2012	685.9	381
Rathi, Maity, Sekhar e Banerjee (2017)	Índia	2016	1,961.6	541
Chen e Lu (2017)	China	2013	2,739.7	737

Source: Elaborated by Camelo (2019), p. 34.

Table 3

Estimated generation of C&DW in Brazilian cities.

Fonte	City / State	Year	Total C&DW (t/day)	*Per capita* rate (kg/inhab/year)
Ceccato (2017)	Caçapava do Sul/RS	2016	6	66
Silva e Marinho (2012)	Juazeiro do Norte/CE	2012	100	120
Tessaro, Sá e Scremin (2012)	Pelotas/RS	2012	404	120
Fagury e Grande (2007)	São Carlos/SP	2007	101	170
Nunes, Mahler, Valle e Glavão (2007)	Rio de Janeiro/RJ	2007	2877	180
Bernardes, Thomé, Prietto e Abreu (2008)	Passo Fundo/RS	2008	101	200
Evangelista, Costa e Zanta (2010)	Salvador/BA	2009	2300	310
Mourão, Aragãoe Damasceno (2015)	Monte Carlos/MG	2013	359	387
Silva, Ferreira, Souza e Silva (2010a)	Goiânia/GO	2009	1500	420
Lorena (2017)	Recife/PE	2014	5260	474
Paschoalin Filho, Faria, Pires e Duarte (2016)	São Paulo/SP	2014	246	520
Silva, Silva, Santos, Souza e Coelho (2010a)	Maceió/AL	2016	2819	848
Costa e Oliveira (2011)	Belo Horizonte/MG	2009	227	920

Source: Elaborated by Camelo (2019), p. 34.

Table 4

Composition of C&DW in selected countries and cities.

Locality	Composition (%)				Source
	Concrete and Mortar	Soil, Sand, and Rocks	Ceramic	Others Materials*	
United Kingdom	9	75	5	11	Industry and environment (1996 as cited in Carneiro et al., 2000, p. 7)
Hong Kong	8	42	12	38	Hong Kong Polytechnic (1993 as cited in Carneiro et al., 2000, p. 7)
Salvador	54	25	19	2	Carneiro et al. (2000)
São Paulo [1]	63	-	29	8	Pinto (1994 as cited in Carneiro et al., 2000, p. 7)
São Paulo [2]	11	83	3	3	Castro (1998 as cited in Carneiro et al., 2000, p. 7)
São Paulo [3]	29	16	13	42	Da Silva and Giacchini (2017)

Note: * Plastic, cans, papers, others

From this table, we can notice the different percentages that make up C&DW. These differences are mainly linked to the executive techniques employed for civil construction. In Brazil, the buildings have higher amounts of mortar and concrete due to ample natural materials such as cement, aggregates, and water. Paschoalin Filho, Storopoli, Guerner Dias, and de Lima

Duarte (2015) point out that given the heterogeneity of material that makes up the C&DW, several international and national kinds of research have been developed and are under development to characterize the primary materials that make up the mass of C&DW. Lima (1999) highlighted that in those cases that there is significant variability of compositions in C&DW, it does not mean that one cannot use the waste as recycles aggregates for pavement layer, coat, non-structural use, or fulfilling gabion basket.

As shown by Versolatto, Paschoalin Filho, and Urnhani (2019) and Almeida, Silva, Formiga, Crispina, de Medeiros, and da Silva (2015), the techniques used in civil construction in underdeveloped and developing countries are traditional and very conservative methodologies. The use of natural resources overlaps with modern technologies and methods. This is due to most of the population's limited knowledge of construction techniques.

For example, in São Paulo, residential real estate developments that use drywall as construction material suffer discrimination from potential buyers. That is happening because walls with concrete blocks or brick have better acoustics and transmit more safety to the environment through high rigidity. However, drywall use is widely applied in civil works in the United States of America and Canada.

To Huang, Wang, Kua, Geng, and Ren (2018), the main barriers to C&DW generation reduction in China are the lack of standardizations for new building design, the absence of public policies, low environmental awareness, and excessive concern about economic issues, and others. According to Paschoalin Filho, Bezerra, Oliveira, and Faria (2017), Brazil is still facing the same obstacles noticed by Huang et al. (2018) in China. The authors also comment that these are widespread limitations in most developing countries.

2.2 CONSTRUCTION AND DEMOLITION WASTES MANAGEMENT

The issue of sustainability and sustainable development are recurrent themes to be discussed in urban planning, given the need for changes in the way natural resources are used by the present generation so that future generations will not be negatively affected.

According to Lasaro (2007), the definition of Sustainable Development was initially presented in 1987 through the Brundtland Report. Since then, reflections on the actual scope and thinking of these sustainability concepts in civil construction to environmental preservation have been presented. Among the central meetings to discuss sustainable development and developmental patterns, we can mention:

a) Club of Rome Report: Limits of Growth (1968);
b) Stockholm Declaration (1972);
c) Brundtland Report: Our Common Future (1987);
d) Rio Declaration (1992);
e) Agenda 21 (1992).

In 1972, during the United Nations Conference on the Human Environment, held in Stockholm/ Sweden, a declaration was generated that defined twenty-seven main objectives to be met, including the right to sustainable development. This resolution addresses current generations' development and environmental issues and development forecasts for countries, including recommendations for taking and eradicating poverty. In 1992, a new declaration was prepared through ECO-92, based in Rio de Janeiro/ Brazil, which reaffirmed Stockholm's previously presented principles and concept. Agenda 21, on the other hand, is another result of the ECO-92 discussions; it is a consensual document signed between the countries, rescuing the term 'Agenda' in its sense of intentions, design, desire for changes for a model of civilization in which environmental balance and social justice prevailed among nations. This treaty aims to affirm Sustainable Development (Lasaro, 2007).

In 2002, the World Summit on Sustainable Development established the Policy Declaration, held in Johannesburg. The declaration defines that Sustainable Development is built on three interdependent and mutually supporting pillars of economic, social, and environmental development (Lasaro, 2007).

Solid waste generation is a problem in developed, developing, and underdeveloped countries; waste management procedures are crucial to sustainability. The C&DW generation without proper management contributes to pressure on landfills increasing, affecting the urban environment. To Wu, Tam, and Zuo (2014), the condition for obtaining good waste management within urban planning begins first with quantifying the C&DW generation. By controlling the generated volumes, it is possible to implement management measures ranging from awareness to education through public policies.

Facing this picture, effective waste management practices must guarantee natural resources maintenance and reduce waste disposal costs and impacts. Effective management strategies like waste generation reduction, reuse, and recycling are necessary to reduce the amount of C&DW disposal in landfills.

Construction and demolition wastes reuse and recycling plays a vital role in implementing circular economy practices. The performing of reverse logistic action for C&DW management is essential to reduce the need for landfills, minimize waste generation, preserve natural resources, reduce demand for raw material, and contribute economic value to the generated waste.

Following these concepts, in 2002, the National Council for the Environment of Brazil elaborated resolution CONAMA n.º 307/2002, which addresses waste according to the type of material, origin, and destination. Guidelines, conditions, and methodologies for C&DW management are defined to reduce environmental impacts. Waste is defined as those derived from civil construction disposal, renovations in general, repairs, demolitions in general, and land and rock (CONAMA, 2002).

To classify the materials, CONAMA n.º 307/2002 initially defined the origins of the waste whether the materials were classified as recyclable and reusable, totaling four classes of materials (A, B, C, and D). This standard underwent a revision in 2004, by the resolution CONAMA n.º 348/2004, for asbestos insertion as a non-reusable and dangerous material. In 2015, through CONAMA n.º 469/2015, the original resolution was changed to incorporate real estate paint packaging in class B of the standard (Camelo, 2019). Table 5 presents the classification according to resolution n.º 307/2002 and CONAMA n.º 469/2015.

In addition to this resolution, technical specifications are available for C&DW management through the Brazilian Association of Technical Standards, Table 6. Although there is no regulation by Infra Constitutional Laws since the law is not obliged to cover every technical detail about all situations, it is given to technical standards legal regulation.

Table 5
C&DW Classification.

Classification	Description	Origin	Materials	Destination
A	Reusable or recyclable waste as aggregates	- Construction process; - Demolition; - Reforms; - Repairs; - Earthwork.	- Asphalt; - Soil; - Bricks; - Bloks; - Tiles; - Cladding boards.	Should be reused or recycled in the form of aggregates, or sent to landfill areas for construction waste, being disposed allow for future use or recycling
B	Recyclable waste for other destinations	- Construction process; - Demolition; - Reforms; - Repairs.	- Plastics; - Paper / cardboard; - Metals; - Glass; - Wood; - Plaster; - Real state paint; - and others.	They must be reused, recycled or sent to temporary storage areas, being arranged so as to allow their future use or recycling
C	Without technologies or economically viable applications that allow their recycling and reuse	- Construction process; - Demolition; - Reforms; - Repairs.	- Plaster	Must be stored, transported and disposed of in accordance with with specific technical standards
D	Hazardous waste	- Construction process; - Demolition; - Reforms; - Repairs.	- Paints; - Solvents; - Oils; - Those contaminated or harmful to health from demolitions, renovations and repairs to radiological clinics, industrial facilities and others; - Tiles and other objects and materials containing asbestos or other products harmful to health.	Should be stored, transported, reused and disposed of in compliance with specific technical standards

Source: CONAMA n.º 307/2002, n.º 384/2004, and n.º 469/2015

Table 6
Brazilian technical standards.

Technical Standard	Títle
ABNT NBR 10.004/2004	Classification of solid waste.
ABNT NBR 15.112/2004	Guidelines for projects, implementation, and operation of transshipment and sorting areas – C&DW and bulky waste.
ABNT NBR 15.113/2004	Guidelines for projects, implementation, and operation of landfills – C&DW and inert waste.
ABNT NBR 15.114/2004	Guidelines for projects, implementation, and operation of areas for recycling – C&DW.
ABNT NBR 15.115/2004	Procedures for paving layer execution - Recycled C&DW aggregates.
ABNT NBR 15.116/2004	Requirements for the use of recycled C&DW aggregates in paving and preparation of concrete without structural function

Source: Camelo (2019), p.40.

As presented by Brum, Berticelli, and Gomes (2017), one of the most useful indicators to evaluate C&DW is concerning aptitude, being divided into three categories:

a) applicable, used in works of soil containment and paving;
b) applicable with restriction, those that require waste laboratory analysis to determine their physical and behavioral characteristics, such as aggregate for non-structural concrete, mortars without structure-function, precast parts of concrete without structural function, draining layers, landfill and gabion filling.
c) not applicable, as a material with structural function. According to Jadovski (2005), those not applicable are justified by restricting current norms and constructive culture.

According to Fernandez (2012), in 2010, Brazil collected an estimated mass of 14 million tonnes of C&DW, where 30% was destined for overflow areas, landfills, and appropriate recycling areas; the remainder was sent to illegal disposals and unauthorized landfills. Fernandez (2012) states that a value of less than 10% of the mass of C&DW has been recycled. Meanwhile, Pereira and Vieira (2013) show that the estimated average for recycling in the European Union is 46%. The highest rate is obtained in the Netherlands, with 98%. Small countries like Cyprus only recycle or reuse their C&DW in 1%.

However, Blaisi (2019) noticed that one of the main difficulties observed in waste management is caused by specific and regional public policies adapted to local needs and not covering a larger scale of influence.

According to Camelo (2019), individual or collective initiatives without government and media support cannot solve the issues of generation and disposal of C&DW. However, an effective way to mitigate environmental damage is strengthening trade that involves recycling and reusing these materials. Similarly, Dorsthorst and Hendriks (2000) present that the recycling of C&DW through management contributes efficiently to reinserting waste into the construction market, reducing, in addition to costs, the environmental impact caused by the works.

In practical terms of management and urban planning, such an example, we have the strategy report for England from Her Majesty's Government (HM Government) (2018), which presents significant urban waste management progress in England. This advance occurred through public policies aimed at waste management over the years, with the concern for separation and investments in energy generation from urban waste. It is predicted that the next step is to overcome waste by managing resources that become waste. Since 1990, the domestic recycling rate has grown four times, and the proportion of waste sent to landfills has fallen to 25%. Meanwhile, the government stresses that England still relies on landfills for waste disposal.

Figure 4 demonstrates the country's evolution of urban waste management through the hierarchy and classification of management types. It is based on an ideal situation where the waste is sent for recycling and recovering. Disposal should be avoided.

Therefore, the measures for C&DW management will only bring benefits to society and the environment. Starting from the example above, in thirty-year, in a developed country like England, there was a substantial change in policies and cultures that enabled the reduction of municipal waste disposal and expanded reuse, recycling, and prevention.

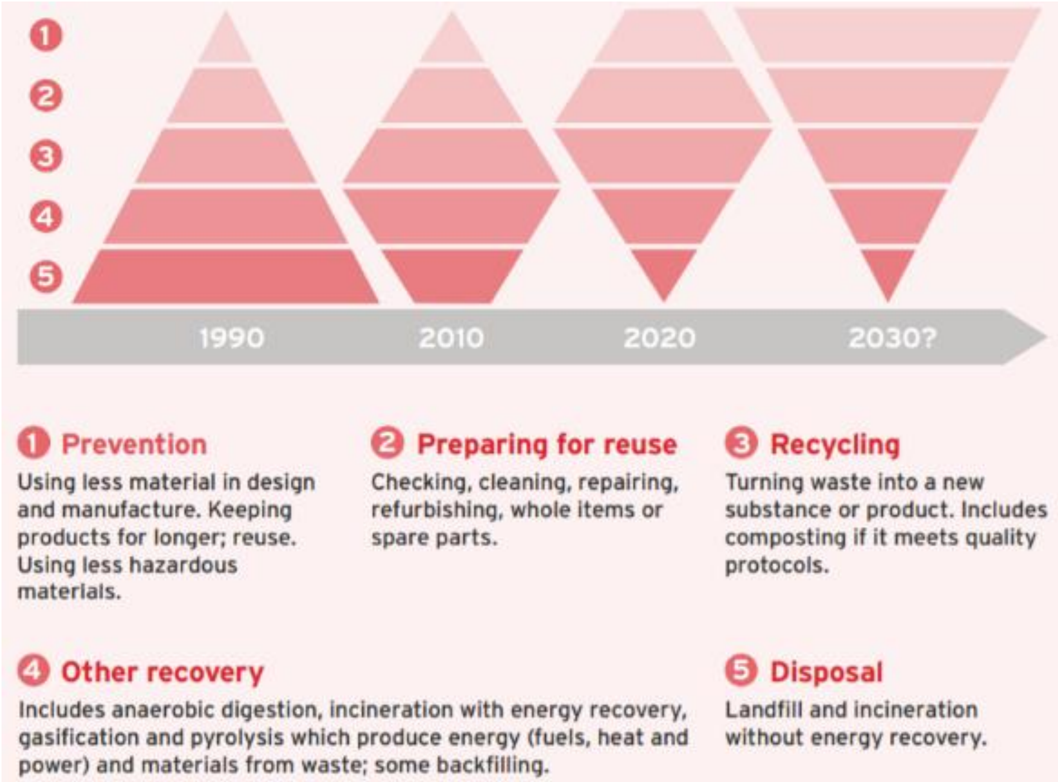


Figure 4. Evolution of waste management practices in England.
Source: HM Government, 2018.

2.3 THE USE OF CONSTRUCTION AND DEMOLITION WASTES FOR CONSTRUCTION WORKS

The authors Camelo (2019), Silva and Fernando (2012), and Paschoalin et al. (2013) present in their work conclusions that demonstrate that the reuse and recycling of C&DW can provide social, environmental, and economic gains. They say that reducing the acquisition of materials for civil construction reduces road transport for disposal, reduces landfill areas, reduces the extraction of natural resources (soil, rock, and water), and reduces harmful gases to health.

Pinto (1999) states that there is proves that C&DW was employed during the Second World War, and after that being applied in the reconstruction of the post-war European continent, later spreading to the other continents. Pinto (1999) points out that the recycling and reuse process has been incorporated through public policies and regulations to create recycling plants in countries like the United States of America and Japan. Additionally, it shows that the first records of C&DW recycling in Brazil go back to the mid-1980s.

Although CONAMA resolution n.º 307/2002 defines the obligation of Municipalities and the Federal District to prepare an Integrated Plan for Construction Waste Management, within a period of up to 12 months and maximum period provided for to cease the disposal of civil construction waste in-home waste landfills was 18 months, according to Brum, Berticelli, and Gomes (2017) the reuse and recycling of C&DW did not materialize in most municipalities in the country, less than 10% of Brazilian cities adopted public measures for the application of C&DW in their civil works.

According to Yang, Du, and Bao (2010), increasing concerns about more sustainable buildings have motivated researchers to develop new waste management tools. The authors have noticed research in Europe and the USA on the use of recycled aggregates in concrete mixing. The obtained data support that these concretes has sufficient compressive strengths for building structures. However, recycled aggregates for concrete mixing are still not allowed by Brazil's technical standards.

Hossain, Xuan, and Poon (2017) evaluated the energy savings obtained during the production of fence blocks from recycled aggregates, getting positive results with a reduced energy consumption of up to 59% compared to the conventional block. Such a reduction in energy consumption is also reflected in the 66% decrease in the air's harmful gases. On the other hand, Silva et al. (2017) determined the utility of the waste from the analysis concerning the compressive and traction resistance for interlocking floors made with recyclable aggregates and crushed unserviceable tires.

Camelo (2019) compiled some emblematic research using C&DW in civil works, focusing on the benefits of materials and aptitude, Table 7. It can be noted that academic research in the field of reuse and recycling of C&DW has been conducted in Brazil for almost two decades, reinforcing the concept of fundamental technological research to reduce the impacts caused by the generation of C&DW.

Figure 5 presents the production sequence for the treatment of C&DW in recycling plants. It shows the initial separation of the material according to physical dimensions, with subsequent removal of any metallic element from the sample and later the material's crushing process until reaching the established granulometric ranges, ranging from a large to a thin aggregate. Thus, C&DW is marketed with a granulometric range similar to natural soils and rocks.

Figure 6 shows the product generated from crushing. In this photo, materials with granulometry between 50mm (gravels) to a diameter of less than 0.5mm (sand) are observed.

Table 7
Some research about the use of C&DW in civil works.

Source	Type of Use	Classification of aptitude of use
Motta (2005)	Light traffic paving	Applicable
Aragão (2007)	Precast Slab	Not applicable
Santos (2017)	Filling, topographic recovery of the land or earthworks.	Applicable
Silva (2009)	Asphalt	Applicable with restriction
Nunes, Mahler e Valle (2009)	Drainage works	Applicable
Nunes, Mahler e Valle (2009)	Slope stabilization	Applicable
Alqedra (2016)	Gabion	Applicable with restriction
Silva, Faria, Fidelis, Campos e Jacob (2017)	Sealing blocks	Applicable with restriction
Santos, Oliveira e Lago (2017)	Bricks	Applicable with restriction
Silva, Calderaro, Cruz e Gonçalves (2017b)	Interlocked floor (*Pavers*).	Applicable with restriction
Bressam, Pires, Soares, Dessuy e Krug (2017)	Structural concrete	Not applicable
Moraes, Bueno, Consatti, Bandeira e Krug (2018)	Mortar	Applicable with restriction

Source: Camelo (2019), p.47.

Analogous to the study presented by Hossain et al. (2017), the city council of Canela, located in the state of Rio Grande do Sul/ Brazil, shows a house model using recycled C&DW material as a structural block for the building of residences of social interest, Figure 7.

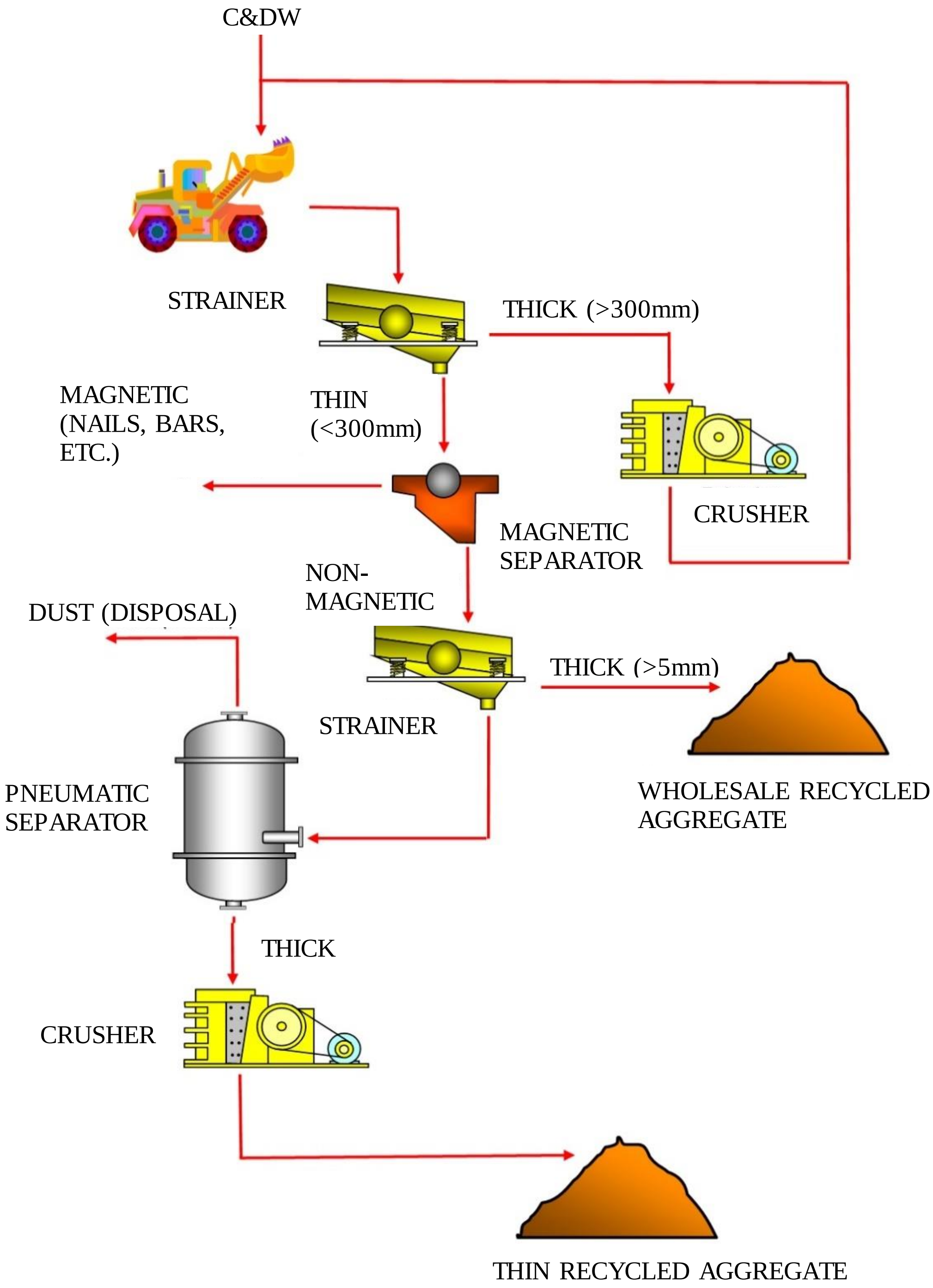


Figure 5. Procedures in a C&DW recycling plant.
Source: from “Reaproveitamento de resíduos sólidos da construção civil no Brasil” by L. Freitas, 2018. *Dom total*.

Figure 6. Recycling material to be used.
Source: from “Reaproveitamento de resíduos sólidos da construção civil no Brasil” by L. Freitas, 2018. *Dom total*.

Figure 7. House model using C&DW recycled material.
Source: from “Alberi Dias solicita criação de Programa de Reutilização de Materiais de Construção”, 2018. Canela City Council.

Among the uses presented, the one that demonstrates greater applicability in Brazil is landfill material arranged in layers (Figure 8). Despite the ease of execution and fast speed for routing the C&DW generated by the process, it is essential to notice that the C&DW are usually not adequately prepared and incorrectly applied. The correct use of the material should be through the particle size variation to reduce voids and improve the landfill layer's compaction with waste.

Figure 8. Landfill material.
Source: from "Use of Recycled Construction and Demolition Waste Aggregate for Road Course Surfacing" by R. Herrador, P. Pérez, L. Garach, and J. Ordóñez, 2012. Journal of Transportation Engineering, ASCE Library.

2.4 THE USE OF CONSTRUCTION AND DEMOLITION WASTE AS FILLING MATERIAL FOR GABIONS

The technical-scientific community has not sufficiently explored the use of C&DW as a filling material for gabion structures. The first Brazilian proposition occurred in 1999 through a suggestion not being materialized in a construction case (Lima, 1999).

According to the studies conducted by Costa (2012), the author verified the technical feasibility of applying C&DW to fill gabions. One of the main advantages determined was the cost reduction of 40% compared to the conventional solution with natural resources. Costa (2012) stresses that the determined viability was only achieved once laboratory tests were carried out for physical characterizations of waste samples. Alqedra (2016) analyzed the use of gabion filled with C&DW, concluding it to be an effective solution and suggesting its applicability for the execution of containments and protections for the construction of housing of social interest.

Paschoalin Filho, Camelo, Carvalho, Guener Dias, and Versolatto (2020) have presented in their research the feasibility of using C&DW for basket gabions filling. The authors noticed that the use of C&DW is an alternative solution for retaining walls execution using gabions based on sustainable principles.

According to Costa (2012), the main disadvantages in using C&DW lie in the aesthetic aspect of the material, since due to the heterogeneity in its composition, shape, and color, the visual character of the set suffers a depreciation and rejection. Maccaferri (2017) states that due to differences in origins and compositions of C&DW, caused by the variability of waste and granulometry produces a different mixture of specific weights to each waste. Resulting in the process of C&DW application as a challenge for use in large-scale civil works.

Figure 9 demonstrates an aesthetic comparison between the gabion filled with natural resources and C&DW; note the difference between the color of the stones and composition.

Figure 9. The aesthetic aspect of the C&DW and natural rock.
Source: Camelo (2019), p. .131.

To evaluate the C&DW, first, we need to determine the behavior of the concrete waste concerning physical, behavioral, and performance characteristics. Then this can be compared with the results obtained for the natural resource.

2.5 GABION

Initially, the gabion solution using metal canvas with stone fill had its origin in Italy, between 1892 and 1893, to recover the Reno river's left margin in Casalecchio di Reno, a town and commune in the Metropolitan City of Bologna. This solution was a concept of Maccaferri Raffaele's Workshop of a blacksmith, based in Zola Predosa (Fracassi, 2017). It results from developing the technology of wire drawing and subsequent metallic wire (Mannucci, 2020). Figure 10 presents works from the beginning of the 20th century in Italy, 1910 and 1923. Figure 11 illustrates dam work performed in Ethiopia in 1937.

According to Frasassi (2017), structures composed of braided plant fiber mesh with stone filling dating from the contemporary epoch to Egyptian civilization were found, about 2,627 b.c. These structures are called "shicras," Figure 12.

Due to military wars, Fracassi (2017) also presents that baskets of wickers filled with stones were created as military barriers to protect soldiers in war camps; Figure 13 shows a barrier during the American civil war in the city of Petersburg/US.

Figure 10. Gabions work in the initial of the 20th decade.
Source: Fracassi (2017).

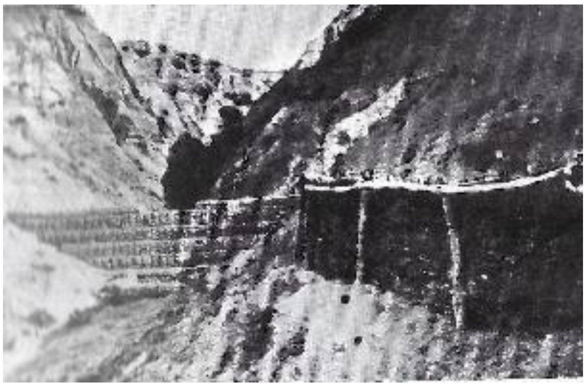


Figure 11. River dam in Ethiopia.
Source: Fracassi (2017).

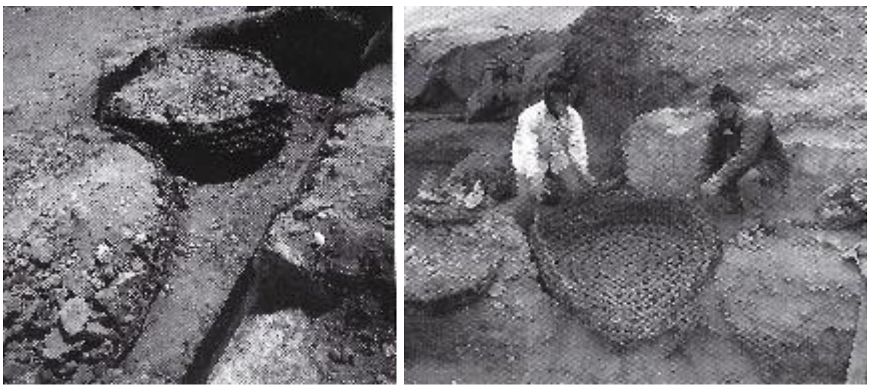


Figure 12. The ancestor of the gabion we know today.
Source: Fracassi (2017).

Figure 13. War barrier during the American civil war, Virginia/ Pennsylvania.
Source: Fracassi (2017).

The gabions are usually filled with natural rocks. These filling materials make the gabion a very draining structure. Because of their flexibility, gabions are recommended for river linings, earth-fill dams, and dissipation stairs. Another characteristic to point out is the dimensions of this kind of gabion. Unlike basket gabions that present a cubic shape, mattress gabions have a length superior to their thickness. Mattress gabion's thickness varies between 0.17 and 0.30m; their length varies between 4 and 6m; the width is usually 2m. On the other hand, the basket gabions have a height and width of 1m and a linear length of 2m.

Mattress gabions have a rectangular shape, where height is determined by the relationship between the flow of water and the filling material's drag resistance capacity. It consists of a double-twist metal mesh with low carbon steel wires with corrosion protection through zinc alloy, with or without coating by a polymeric material layer (depending on whether or not there is contact with water), which provides corrosion protection and protects against mechanical damage caused by stroke or wears.

Figure 14 shows a gabion assembly. Figures 15 and 16 present river claddings executed with gabions.

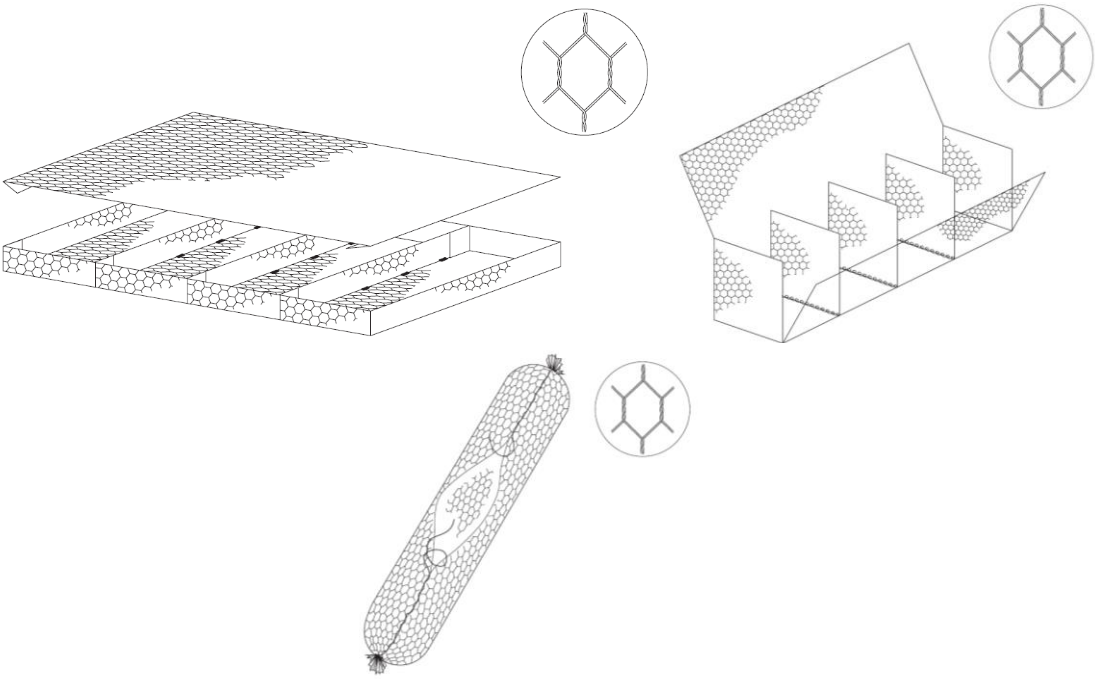


Figure 14. Gabions assembly.
Source: Maccaferri (2020).

Figure 15. Gabion was used for river cladding.
Source: Maccaferri (2020).

Figure 16. Gabion was used for river cladding under a bridge.
Source: Maccaferri (2020).

Depending on the deployment conditions, you can assemble and fill the gabion in another safe location. Subsequently, lifting the piece is placed to protect the margin and bottom. Another use for gabion is when you have specific situations, such as a low longitudinal slope. You can apply mortar on the gabion surface to increase the flow rate by reducing the cladding's roughness coefficient. In this case, the set will exhibit semi-rigid structural behavior.

2.5.1 Rivers, streams, and cladding

As presented, one of the primary forms of illegal disposal of C&DW, and other wastes, is along beds of streams, rivers, and idle land. This fact occurs due to ease of access through the margins, especially in unoccupied areas. In places with high demographic density, the disposal occurs due to the absence of education, social lack of knowledge, and ignorance about the harmful effects that such an attitude may cause.

The natural and artificial water network has many practical applications in the city, including sanitation, urban drainage, irrigation, energy generation, navigation, and conservation of the environment.

By definition, humans design or deploy artificial channels, such as navigation channels, power generation, irrigation, macro surface drainage, water supply, scale laboratory models, etc. In this way, hydraulic characteristics are known and adopted, meeting prerequisites and future needs satisfactorily for practical purposes of design and work (Chow, 1959).

According to Maccaferri (2017), in works of recovery or protection of urban rivers and streams, the implementation of cladding on the margin can correspond to 25% of the work's total value. Thus, decision-making on which cladding is the best to be used is extremely important since its performance will ensure the work's service life through efficient protection against wear generated by water speed and drag stresses.

Usually, the gabion is implanted in natural channels to recover the section originates or rectification and artificial channels. Based on hydraulics' theoretical foundations, the solution's design conditions will be presented and discussed to support and characterize the gabion solution.

The gabion design should consider the stability condition, represented by the balance of water flow - direction, trajectory, time, and rotation - and the erosive process of the material constituent of the hydraulic section. The natural balance can be changed from increased water flow and advanced erosive processes – natural corrections generated by the watercourse (Maccaferri, 2017).

Any modification that occurs directly in the rivers or channel section – rectification, alteration of the channel cladding, dam, or other - or indirectly through intervention in the basin contribution - deforestation, urbanization, and alteration of land use - will cause a change in the natural condition of the flow regime. These changes will reflect an increased flow rate, advanced erosive processes, flooding, and silting. Thus, applying protective elements on rivers, streams, channel banks, and the bottom is necessary to maintain the desired watercourse, reduce erosive processes, and protect the infrastructure in or beside the watercourse (Maccaferri, 2017).

Another essential factor for the cladding specification is the kind of soil foundation. Depending on its composition and behavior properties, it may present conditions that make it impossible to apply specific techniques.

In the Cenozoic era, the rivers and streams emerged, about 1.8 – 2.58 million years, from the glaciation process interspersed for warmer periods. With the evolution of the transgressive-regressive process of changing the seawater level, the continental plains were formed, and erosive processes caused the river channels' deepening. With the transgressions, seawater promoted sandy and sandy-clay sediments deposition in rivers, bays, and lagoons (Souza, Vidal-Torrado, Tessler, Pessenda, Ferreira, Otero, and Macias, 2007).

Because the soil formation is through the sedimentation of particles, organic decomposition matter, and marine sediments, the surface layers with higher clay content suffer from vertical and horizontal deformations over time. That is due to soil voids and type of mineral clay composition, reflecting insufficient support capacity as a direct foundation. However, despite presenting fluffy compactness, the stratigraphic layers composed of sand, when receiving a load due to cladding or surface drainage device, show an initial spatial deformation followed by stabilization displacements. The channel and rectification works can transpose better quality soil layers or even promote the removal of compressible soil from the foundation.

Maccaferri (2017) argues that for works of protection of watercourses, it is possible to carry out the division by the following criteria:

a) Continuous or direct protection, where the cladding is to be used, has stiffness characteristics superior to the natural terrain that makes up the margins and bottom. E.g., Mattress gabion, basket gabion; mortared stone, geomat, others;
b) Discontinuous or indirect protection, use of devices to break water energy, reducing speed. However, this does not prevent the formation and advancement of erosive processes. E.g., bag gabion, basket gabion, mattress gabion, concrete structures, others;
c) Support works consist of implementing vertical containments of the land massif along the margin. The primary purpose is to support the earth's buoyancy from the ground due to the hydraulic section's rectification, resisting the flow and wave effects, depending on the case. E.g., gabions, concrete structures molded on-site or precast, geotextiles filled with soil or mortar.

2.5.2 Filling

According to the Brazilian technical specification that governs road infrastructure works in the state of São Paulo (ET-DE-H00/012, 2006), the filling material must originate from healthy rock, not be friable and present the requirements required by the standard for crushed stone. The filling of a resistant material and specific high weight does not allow decompose materials. The granulometric range must be the one with diameters between one and a half and two and a half times the mesh's maximum opening.

In this way, the C&DW to be used must be obtained from crushing and quality classification, consisting of rugged, clean, and durable fragments, free of particles of easy disintegration and harmful substances or contaminations. The filling is made from the structure's assembly of the hexagonal mesh on a flat, rigid, and organic matter-free surface. The assembly process demands three people's labor. Two people perform the manual placement and arrangement of the stones inside the mattress. The third person monitors and verifies the accommodation of the rocks.

The executive care in the arrangement and arrangement of the filling is essential to obtain an empty value of less than 30% of the total volume. If this criterion is not met, water flow may occur the drag of the fill and cause deformations in the cladding (Maccaferri, 2017).

2.5.3 Applications and design

The flow is characterized by atmospheric pressure, spatial and temporal variation, hydraulic section, and roughness in coats and rivers. Their characteristics may lead to stability problems along the lateral and bottom slopes, particle carrying, salting, siltation, and floods.

Comparatively analyzing open channels and closed pipes, we have that the design methodology of the treatment of margins and bottom is based on experiments and observation, empirically, obtaining satisfactory results for practical application issues. Such statements allow the use of hydraulic theories to process data and get analytical values. Additionally, the study of the behavior of flow in natural channels requires the knowledge of other areas of expertise - such as hydrology, geomorphology, sediment transport, geotechnics, others - constituting a proper theme called "river hydraulics" (Chow, 1959)

The hydraulic section is the geometric cross-section of the watercourse, corresponding to the wet perimeter, and may vary according to the river, stream, or channel flow. Table 8 shows some definitions of flow regimes, according to (Chow, 1959).

Table 8
Flow regimes.

Variable	Flow regime	Description
Direction	Laminar	The water particles run parallel paths in a lamellar shape.
	Transitional	It consists of a laminar flow close to the edges and the channel's central region's turbulent regime.
	Turbulent	The trajectories are irregular - curved or non-parallel - with intersections causing strong and rotating movement (vortex).
Time	Permanent	Flow with constant speed and pressure (due to hydraulic load) throughout the sections, without time variation. Stably.
	Non-permanent	Water pressure and speed are dependent on position and time. E.g., Water tower.
Trajectory	Uniform	At different analysis points, the trajectory remains the same, without speed changes, the way and direction remaining constant.
	Miscellaneous	The points of the same trajectory show differences in speed over some time. E.g., the holes in a watering can.
Rotation	Rotational	The water particle is subject to angular velocity concerning its center of mass.
	Non-rotational	It is the one in which the rotational behavior of the flows is disregarded, where the deformable particles are considered, neglecting the influence of viscosity and improving the mathematical conception of the flow.

Source: Chow (1959), pp. 5-15.

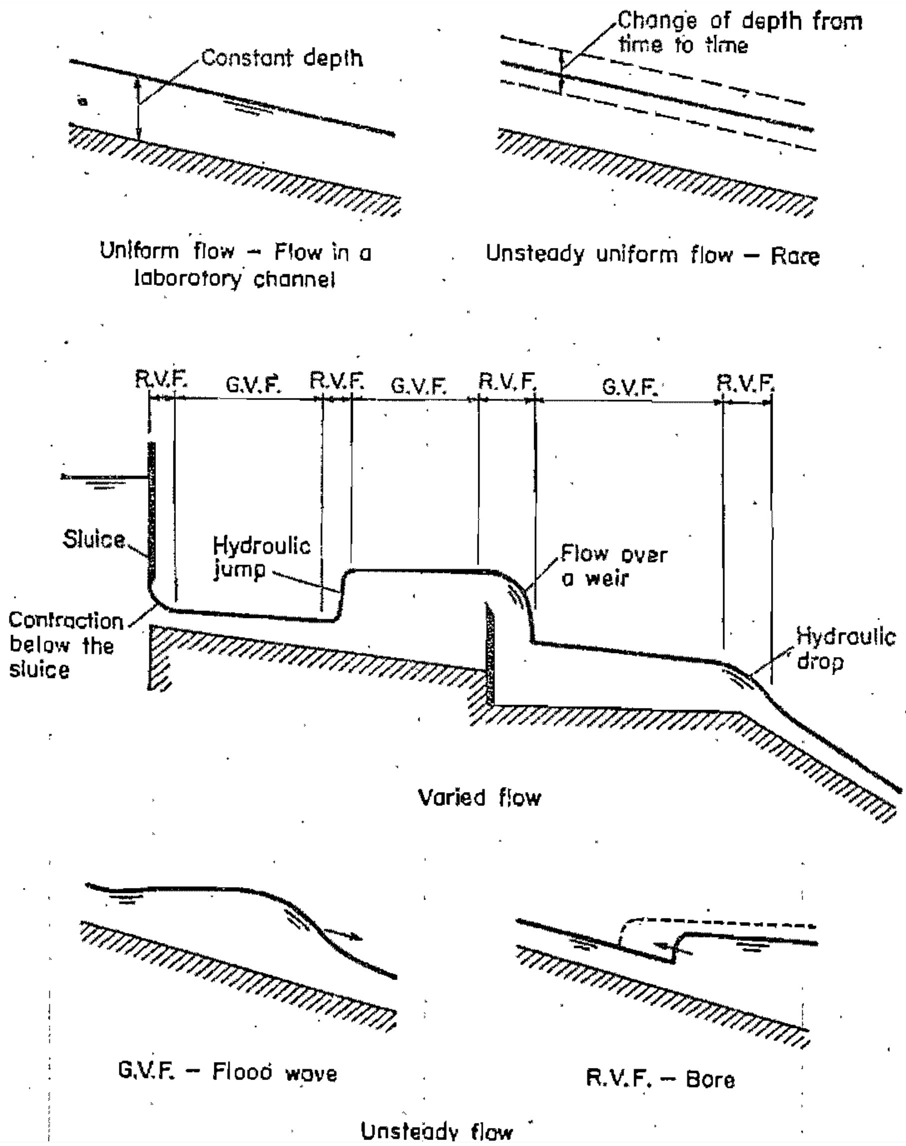


Figure 17. Flow’s types.
Source: Chow (1959).

A good performance is defined from the conditions of slope, geometry, potential energy, and surface roughness coefficient. Among these parameters, the roughness coefficient is the one that shows the most considerable variability. Since the channels' walls and bottom are heterogeneous, the material variation influences the flow. A direct determination can be highlighted by calculating or estimating the hydraulic section's characteristics based on the materials' granulometry that constitutes the channel's bottom and walls. Another way is through the formulation proposed by Manning.

Usually, artificial channels have a triangular geometry, vertical rectangular or trapezoidal. The sections of natural channels are naturally irregular, with section geometry ranging from a parabola, a round-base triangle, to a trapezoid. In some cases, where the adjacent terrain is a flat and low slope, river floodplains, the channel section can increase substantially in size in periods of a flood by increasing the volume of water and transshipment (Chow, 1959).

For the distribution of velocity along the canal or river section, we have the geometric cross-section, the roughness of the walls or margins and bottom, and curves as conditioning factors. The maximum speed can be found near the surface in fast flow channels and low water height or low slope. On the other hand, the velocity tends to increase on the cross section's convex side due to the water flow's centrifugation. Figure 18 demonstrates speed behavior along some hydraulic sections (Chow, 1959).

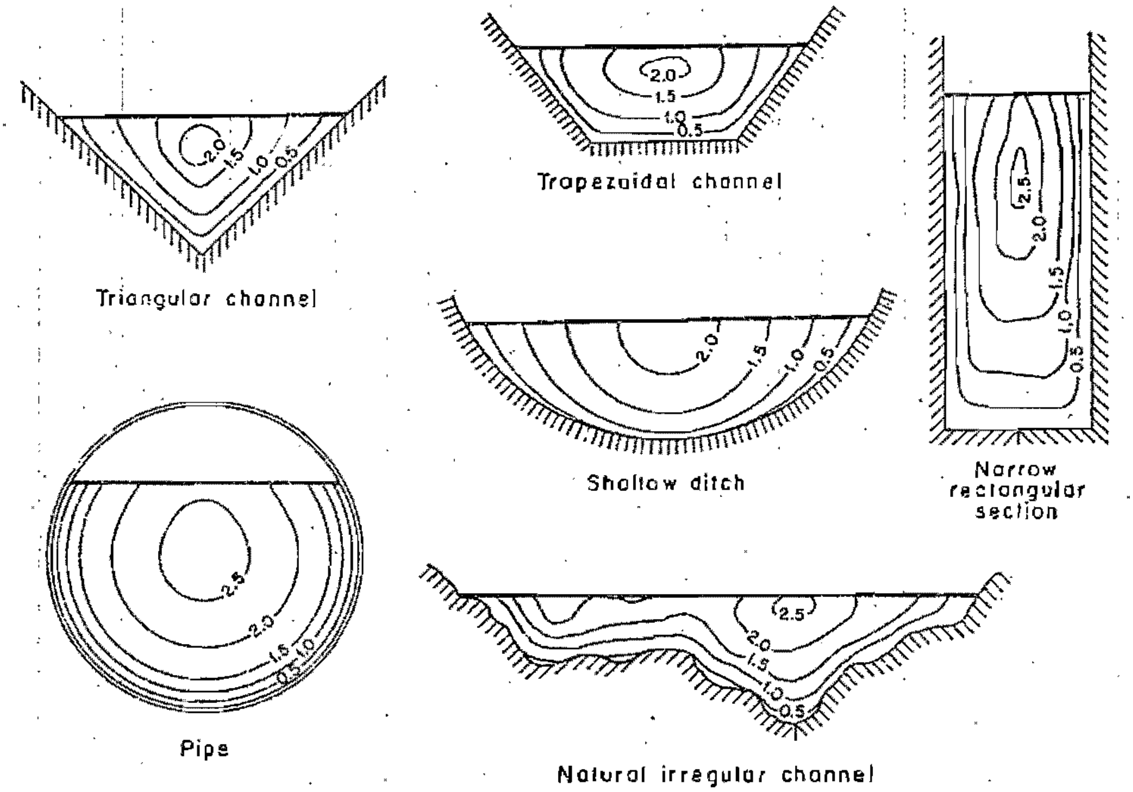


Figure 18. Velocities along which channel section.
Source: Chow (1959).

Due to the design and physical heterogeneity of the land, the uniform permanent regime is used to elaborate recovery, rectification, or channeling projects. This regime makes it possible to obtain a satisfactory calculation based on the hydraulic section's homogenization and the absence of interference in the upstream and downstream flow of the calculated stretch. Figure

6 presents a schematic picture prepared by Maccaferri (2017). The formulations of area calculation, wet perimeter, and hydraulic radius for different section types are presented.

Hydraulic channel sizing is based on flow resistance equations, which relate load loss in a stretch to average speed or flow rate. Through the basic concepts of hydraulics, we have that the flow formula (1) is the product between the flow rate (V) and the cross-section area for the direction of the flow (A). The hydraulic radius (2) is the result of a division between the area (A) and the wet perimeter section (P).

$$Q = V . A \ (1)$$

$$R_H = \frac{A}{P} \ (2)$$

In 1769, the French engineer Antoine de Chézy proposed an equation (3) to determine the flow rate from the product between the Chezy coefficient “C” (4) – friction factor generated in the canal due to roughness -, hydraulic radius and longitudinal slope. Chow (1959) stresses that the proportion of weight forces represents weight's effect on the flow state.

$$V = C . \sqrt{R_H . j} \ (3)$$

$$C = \sqrt{\frac{8 . g}{f}} \ (4)$$

Where:

j= energy declivity.

g= gravity acceleration.

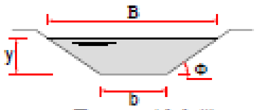
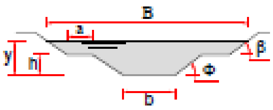
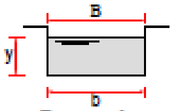
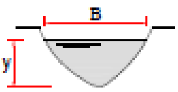
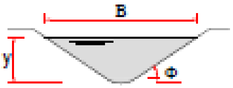
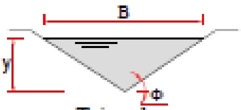
f= friction.

$$\frac{1}{\sqrt{f}} = 2 . \log\left(\frac{14.84 . R_H}{\varepsilon}\right) \ (5)$$

Where:

ε= equivalent roughness coefficient

Due to calculation simplifications for sizing, it is not usual to calculate a channel stretch's adoption with an equivalent hydraulic roughness. From Maccaferri (2017), the formulations (3), (4), and (5) are enough to determine the characteristics of the channel to be designed.

Section	Area (A)	Wet Perimeter (P)	Hydraulic radius (R_H)
 Trapezoidal (i)	y . (b + y . cot Φ)	b + 2y / sen Φ	y . (b + y . cot Φ) / (b + 2y / sen Φ)
 Trapezoidal (ii)	(b + 2a) . y + y^2 . cot Φ - 2ah) **	b + 2a + 2y / sen Φ **	[(b + 2a) . y + y^2 . cot Φ - 2ah] / b + 2a + (2y / sen Φ) **
 Rectangle	b . y	b + 2y	b . y / (b + 2y) ***
 Parabola	⅔ B . y	B + ⁸⁄₃ . y^2/B ****	$2B^2$. y / ($3B^2$ + $8y^2$) ****
 Round base triangle	(B^2 tan Φ) / 4 - r^2 . tan Φ + r^2 . Φ (*)	[B / (Φ . cos Φ)] - 2r . tan Φ + 2r (*)	[(B^2 . tan Φ / 4) - r^2 . tan Φ + r^2 . Φ] / (B/cos Φ) - 2r . tan Φ + 2r . Φ (*)
 Triangle	y^2 . cot Φ	2y / sen Φ	(y / 2) . cos Φ

Note:

* In radians

** β = Φ

*** When B >> y, then R_H = y

**** If

$0 < x < 1 \rightarrow x = 4y/B$

$x > 1 \rightarrow C = (B/2) . [\ 1 + x^2 + 1/x . \ln (x + \ 1 + x^2)]$

Figure 19. Determination of areas, wet perimeters, and hydraulic radius.
Source: Maccaferri (2017).

In 1889, Robert Manning proposed an equation for determining the Chézy coefficient from the relationship (6) between the hydraulic radius and an "n" number. The coefficient "n" was obtained from Manning's experimental analyses, in which the function is a constant for a certain roughness. This formula enables us to understand that the flow can be permanent, uniform, and turbulent rough. However, Maccaferri (2017) considers that the Manning coefficient presents a disadvantage because it does not have a dimensional coefficient. Its formulation is based on empirical results and does not have an exact physical meaning. Despite these points, it is possible to determine a relationship between the Manning coefficient (n) and the equivalent roughness coefficient (ε) (Maccaferri, 2017).

$$C = \frac{R_H^{1/6}}{n} \quad (6)$$

$$V = \frac{1}{n} \; . \; R_H^{2/3} \, . i^{1/2} \quad (7)$$

According to Soares (2012)) the hydraulic section of rivers and streams presents roughness heterogeneity; thus, it is necessary to determine a single roughness coefficient. Figure 21, associated with equations (8) and (9), gives the methodology for defining an average coefficient according to the hydraulic section. Table 9 shows a review of Manning's roughness coefficient values.

$$n = \left[\frac{\sum_{i=1}^{m}\left(P_i n_i^{3/2}\right)}{P}\right]^{2/3} \quad (8) \qquad n = \frac{\sum_{i=1}^{m} n_1 A_i}{A} \quad (9)$$

Where:

n= overall roughness coefficient.

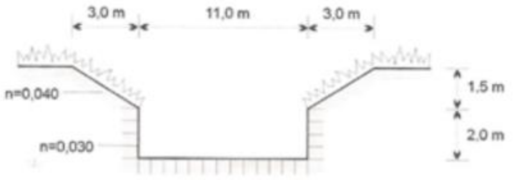
P= wet perimeter.

Pi= wet perimeter associated with surface "i."

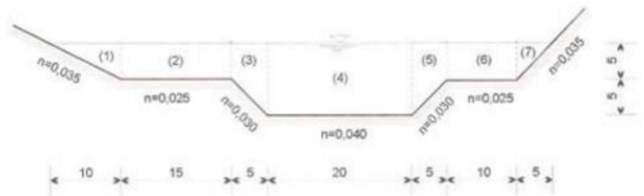
ni= roughness coefficient associated with surface "i."

A= total area.

Ai= area associated with surface "i."



(a) Variation of roughness about the wet perimeter



(b) Composite section

Figure 20. Different section's roughness.
Source: Soares (2012), p. 6.

From the definition of the channel geometry and coating to be applied, it is necessary to verify a cladding's stability according to speed and drag stress criteria. The goal is to evaluate whether the average speed is less than the critical speed or limit speed supported by the coating. Similarly, the generated drag tension (τ0) and the channel cladding's critical tension (τ0.c) are determined.

$$V_{average} \leq V_C \ (10)$$

$$\tau_0 \leq \tau_{0,C} \ (11)$$

The coating is defined as stable when no displacements and deformations of the set are formed by the hexagonal mesh and filling material. Maccaferri (2017) points out that the magnitude of the hexagonal mesh's resistance is superior to the friction between the filling particles - confining the filling material in the mattress gabion. There is an understanding that the resistance can be increased.

Table 9

Particle sizes and mass for testing procedures.

Type of cladding Conditions of the cladding	Good	n ($s.m^{1/3}$) Medium	Bad	Source
Channels lined with Reno® mattresses and covered with mortar.		0.013		Maccaferri (2017)
Channels lined with Reno® mattresses perfectly waterproofed with hydraulic bitumen mastic applied with particular methods to obtain a flat and very smooth surface.		0.0158		
Channels lined with Reno® mattresses and box gabions perfectly waterproofed with directly applied hydraulic bitumen mastic.		0.0172		
Channels lined with Reno® mattresses and box gabions consolidated to the surface with hydraulic bitumen mastic surrounding the surface stones.		0.020		
Channels lined with Reno® mattresses and box gabions consolidated with hydraulic bitumen mastic that penetrates in depth.		0.0215		
Channels lined with Reno® mattresses filled with well-selected material and placed on-site with great care.		0.0222		
Channels lined with Reno® mattresses filled with well-selected material and placed on the job without care.		0.0250		
Channels lined with Reno® mattresses filled with unselected quarry material and placed on-site without care.		0.0270		
Channels are lined with box gabions filled with well-selected material and carefully placed on site.		0.0260		
Channels lined with basket gabions filled with well-selected material and placed on the job without care.		0.0285		
Channels in poor maintenance conditions: entanglement of vegetation at the bottom and on the banks; or irregular deposits of stones and gravel; or deep irregular erosions. Also, channels are executed with machines, a mechanical excavator, and careless maintenance.		0.0303		
Natural watercourses, with rounded stone bed and material movement		0.0480		
Mortar stone	0.017	0.025	0.030	Porto (1998 as cited in Piza, 2013) and Cirillo et al. (2001 as cited in Piza, 2013)
Brick masonry	0.012	0.015	0.017	
Smooth metal gutters (semicircular)	0.011	0.013	0.015	
Open channels with rock (irregular)	0.035	0.045	-	
Channels with a bottom on land and embankment with stones	0.028	0.033	0.035	
Channels with a rocky bed and vegetated slope	0.025	0.035	0.040	
Concrete channels	0.012	0.016	0.018	
Earth channels (straight and uniform)	0.017	0.023	0.025	
Gabion	0.022	0.035	-	
Cement mortar surface	0.011	0.013	0.015	
Smoothed cement surface	0.010	0.012	0.013	
Clean, straight, and uniform streams and rivers	0.025	0.030	0.033	
Clean, straight, uniform streams and rivers with stones and vegetation	0.030	0.035	0.040	
Clean streams and rivers with meanders, banks, and wells	0.035	0.045	0.050	
Spread margins, little vegetation	0.050	0.070	0.080	
Spread margins, lot of vegetation	0.075	0.125	0.150	

Tangential drag tension

In channels where the water flow has a permanent and uniform flow regime, the tangential drag stress generated at the bottom of the channel is calculated (12).

$$\tau_0 = \gamma_w \,.\, R_H \,.\, i \; (12)$$

Where:

γw= specific water weight (10 kN/m³).

RH= hydraulic radius of the section (m - meters).

i= longitudinal slope of the canal's bottom (m/m).

However, as Maccaferri (2017) presents, in cases where there is a relationship between the width of the channel and depth equal to or greater than 30 – such as in urban rivers – it is possible to assume that the hydraulic radius is equal to depth. In cases where the ratio is less than 30 and greater than 8, Maccaferri (2017) recommends equalizing R_H with y since this consideration favors safety, reflecting in an action of the flow of greater magnitude.

$$\tau_0 = \gamma_w \,.\, y \,.\, i \; (13)$$

When we have the width and depth ratio below 8, we consider applying a correction coefficient (Kf) to reduce the difference between the hydraulic radius (RH) and the depth (y). The proposed correction coefficient arose from the study conducted by Lencastre in 1983 to determine tangential tensions related to the canal's margin.

To determine the critical tangential stress ($\tau_{0,C}$) (14) that the coating supports, the coefficient proposed by Shields (C) will be taken into account, in which it relates the frictional force of the fluid on the grain and the submerged weight of the grain. Shields' research focused on analyzing the origin of the movement of sediment particles.

$$\tau_{0,C} = C \,.\, (\gamma_S - y_W) \,.\, d_m \; (14)$$

Where:

γw= specific water weight (10 kN/m³).

γs= specific rock weight (kN/m³).

dm= average diameter of the bottom material (m).

C= Shields coefficient (For gabion C ≈ 0,10).

In the case of the mattress gabion, Maccaferri (2017) presents that from research in natural and reduced scale models, the value of the Shields parameter obtained experimentally was: C ≈ 0.10. Comparing the result to the Shields coefficient of a large rock (0.20 to 0.60 m) valor of approximate value of 0.047, Maccaferri (2017) attributes the difference in values to the presence of the hexagonal mesh provides confinement for the filling stones.

In the margin calculation, the calculation considerations change due to differences in tangential drag stresses' distribution. Usually, a coefficient of 0.75 is used to reduce the stress about the value obtained for the bottom of the channel. However, Maccaferri (2017) presents the consideration of the adoption of the methodology proposed by Lencastre for the adoption of a correction coefficient in the calculation of tangential stresses active($\tau 0$) and (τm) and critic sizes ($\tau \tau m,c$), based on the slope of the margin slope (m), bottom width (b) and height of the water lamina (y), Table 10.

$$\tau_0 = K_f \, . \, \gamma_w \, . y \, . \, i \; (15), bottom$$

$$\tau_m = K_m \, . \, \gamma_w \, . y \, . \, i \; (16), margin$$

$$\tau_{m,C} = \tau_{0,C} \, . \sqrt{1 - \frac{sen^2\alpha}{sen^2\omega}} \; (17), margin$$

$$\tau_m \leq \tau_{m,C} \; (18)$$

Where:

α= margin inclination angle

ω= internal friction angle of the cladding filler.

Table 10
Correction coefficient.

b/y	m					
	2		1,5		0	
	Kf	Km	Kf	Km	Kf	Km
0	0	0.650	0	0.565	0	0
1	0.780	0.730	0.780	0.695	0.372	0.468
2	0.890	0.760	0.890	0.735	0.685	0.686
3	0.940	0.760	0.940	0.743	0.870	0.740
4	0.970	0.770	0.970	0.750	0.936	0.744
6	0.980	0.770	0.980	0.755	-	-
8	0.990	0.770	0.990	0.760	-	-

Source: Lencastre (1983, cited in Macafferi, 2017, p.41).

Critical Speed

Another criterion for verifying a channel's stability concerning flow is verifying the critical - or maximum - permissible speed to ensure that the filling does not move along the section. According to Lencastre, it is usually impossible to determine the critical velocity at the bottom, and therefore, it is custody to adopt the average flow rate (Maccaferri, 2017).

For channels of average flow rate and equal coating but with different depths, the velocity tends to be higher with less water lamina. Thus, the method to be applied to calculate the critical velocity should consider the different depths of the flow. From the research carried out by Maccaferri (2017) in the hydraulic laboratory of Colorado State University, the flow speed causes the beginning of the displacement of the particles of the filling in relation to the gabion's thickness mattress was experimentally determined. Table 11 summarizes the values obtained and recommended by Maccaferri (2017) for practical sizing purposes.

Table 11

Correction coefficient – Critical Speed.

Mattress gabion thickness (m)	Size rock filling		Critical speed (m/s)
	Dimension (mm)	d50 (m)	
0.17	70 - 100	0.085	3.5
	70 - 150	0.110	3.8
0.23	70 - 100	0.085	3.7
	70 - 150	0.110	4.1
0.30	70 - 120	0.100	4.0
	100 - 150	0.125	4.3

Source: Macafferri (2017, p.46.

3 MATERIAL AND METHODS

In Figure 21, a schematic overview of the performed methodology for this research is shown.

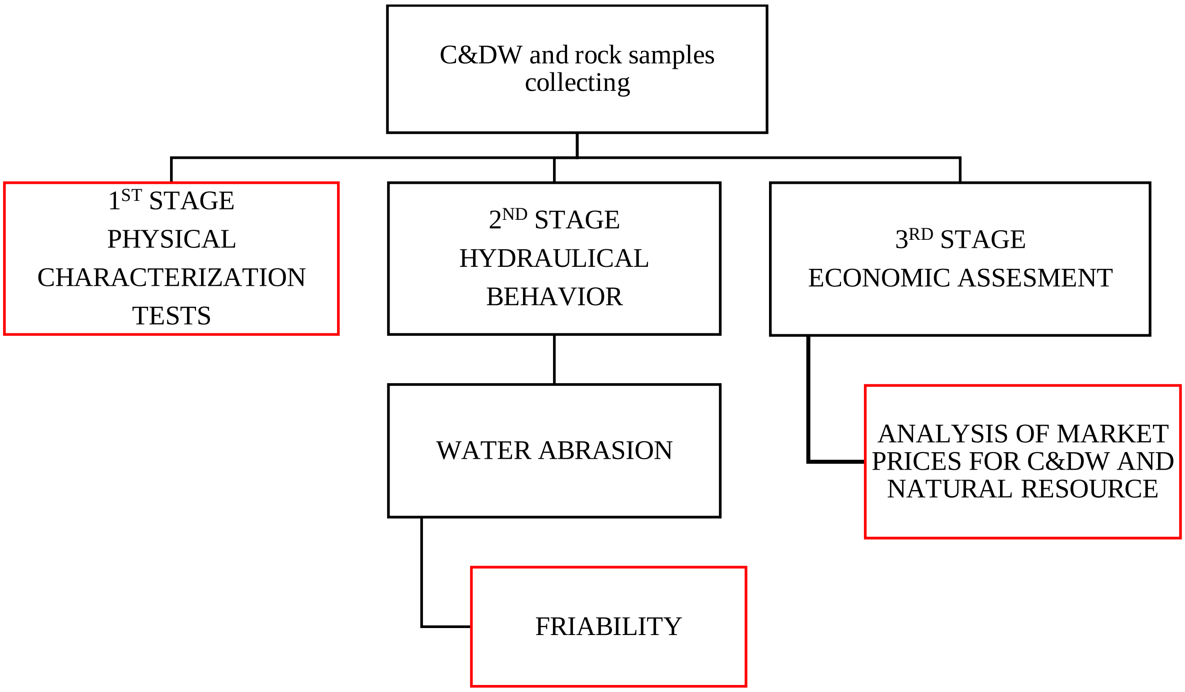


Figure 21. The proposed methodology for the study.

3.1 C&DW AND ROCK SAMPLES COLLECTING

Coarse samples were collected at a C&DW Recycling Plants near the city of São Paulo. The samples were gotten from different piles, and after that, they were dried and packed. The collected coarse samples were composed only of concrete wastes between 7 and 15 cm, as required by Brazilian Technical Standards. Figures 22 to 24 present the collection procedures performed. The rock coarse samples were collected at the same recycling plant as the C&DW wastes.

Figure 22. Rock coarse samples pile.

Figure 23. C&DW pile.

Figure 24. Samples washing and packing.

3.2 PHYSICAL CHARACTERIZATION TEST

The laboratory tests were performed as Brazilian and International Technical Standards requirements as ABNT, AMN, and ASTM. The tests and the technical standards are the following:

Table 12
Performed laboratory tests and technical standards

Test	Technical Standard
Determination of specific weight, coarse apparent specific weight, and absorption test	AMN NM 53
Los Angeles Abrasion	ASTM C131 and AMN NM 51
Durability test	ASTM C1218, ASTM C88-76 and DNER-ME 089
Shape index	ABNT NBR 7809
Water abrasion	Non-standard

3.2.1 SPECIFIC WEIGHT, APPARENT SPECIFIC WEIGHT, AND ABSORPTION TESTS

The AMN NM 53 (2009) presents the methodology for specific weight, apparent specific weight, and absorption. The specific weight (d) was obtained by equation (19).

$$d = \frac{m}{m - m_w} \tag{19}$$

Where:

m= sample mass (g);

m_w= water mass (g)

Equation (20) determines the aggregate's specific weight with a dry surface (ds) in the saturated condition.

The apparent specific weight (da) and the absorption values were obtained using the following equations. Figures 25 to 28 show the procedures performed for apparent specific weight, specific weight and absorption tests.

$$d_s = \frac{m_s}{m_s - m_w} \text{ (20) (kN/m}^3\text{)}$$

$$d_a = \frac{m}{m_s - m_w} \text{ (21) (kN/m}^3\text{)}$$

$$A = \frac{m_s - m}{m} \times 100 \text{ (22) (\%)}$$

Figure 25. Water immersion (C&DW and rock coarse soil samples).

Figure 26. Saturated samples with the dry surface (C&DW and rock coarse soil samples).

Figure 27. Coarse samples paraffin wrapping.

Figure 28. Bulk determination (C&DW and rock coarse soil samples).

3.2.2 SHAPE INDEX DETERMINATION

The shape index was found according to the Brazilian Technical Standard ABNT/NBR 7809 (2019) requirements. For this, a caliper rule with an accuracy of 0.1mm was used. The test was carried out for one hundred C&DW and coarse rock grains. The caliper rule was used for grains' length (c) and thickness (e) measurements. The index shape was found by equation 23 using.

$$I_{Shape} = \frac{c_{Medium}}{e_{Medium}} \quad (23)$$

Figure 29. Rock sample shape index obtention.

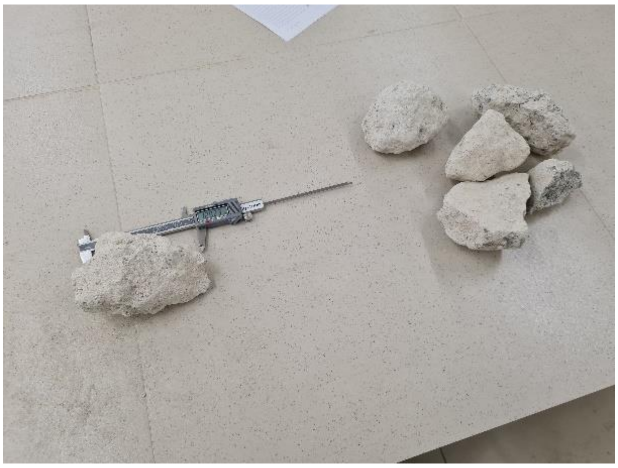


Figure 30. C&DW sample shape index determination.

3.2.3 Los Angeles abrasion test

According to the technical specifications NM 51 (2000) and ASTM C131/C131M (2014), the "Los Angeles" abrasion test is used to obtain the degradation degree of coarse aggregates under abrasive efforts. This way, coarse samples are put into a rotative steel drum with many spheric balls inside.

Due to limitations concerning the particle size of the material to be tested, C&DW particles with lower dimensions were used (Sample type “E”), taking into account the following granulometry and mass, Table 13.

The sample is dried before on a stove at 107 ± 2.5 ºC. The sample remains on the stove until it gets constant mass. It means that all water inside the sample porous was evaporated, remaining only grains and air.

After drying, the sample amount is mixed under the criteria shown in Table 13. So, the sample amount is put into the rotative drum with some steel spheres (the number and diameter of the spheres are chosen according to sample amount grain size distribution). As the drum ends its spinning, the samples are taken out and passed through a # 12 sieve (1.7mm mesh). The retained sample amount is washed and dried again.

Table 13
Particle sizes and mass for testing procedures.

Sieve opening (mm) Material		Mass of indicated sizes (g) Grading						
Passing	Retained on	A	B	C	D	E	F	G
75	63					2,500 ± 50		
63	50					2,500 ± 50		
50	37.5					5,000 ± 50	5,000 ± 50	
37.5	25	1,250 ± 25					5,000 ± 25	5,000 ± 25
25	19	1,250 ± 25						5,000 ± 25
19	12.5	1,250 ± 25	2,500 ± 10					
12.5	9.5	1,250 ± 25	2,500 ± 10					
9.5	6.3			2,500 ± 10				
6.3	4.75			2,500 ± 10				
4.75	2.36				5,000 ± 10			
Total (g)		5,000 ± 10	5,000 ± 10	5,000 ± 10	5,000 ± 10	10,000 ± 100	10,000 ± 75	10,000 ± 50
Drum rotation		500	500	500	500	1,000	1,000	1,000

Source: AMN NM 51 (2000), p. 5.

The following equation gives the percentage of lost material by the abrasion efforts. Figure 31 presents the being performed.

$$P = \frac{M_{initial,dry} - m_{sieve,dry}}{M_{initial,dry}} \times 100 \qquad (24)$$

(a) (b)

Figure 31. Los Angeles abrasion test being performed

3.2.4 Coarse samples durability Assessment using sulfate sodium solution

This laboratory test was performed to assess the wear suffered by the coarse aggregates of C&DW and rock under sodium sulfate attack. The tests were performed under the requirements of DNER-ME 089 (1994) (Brazilian Department for Road Design and Execution).

The laboratory test procedure consists of leaving the coarse samples in a container with sulfate sodium solution for 18 hours. The container must be adequately covered to prevent solution contamination. After that, the samples had to be dried in an oven with 105 to 110ºC until they got mass constancy. Figure 32 shows the sodium sulfate and the containers used.

Figure 32. Sodium sulfate and containers used in the laboratory test.

This immersion process in the solution, washing, and drying should be carried out in continuous cycles at the researcher's discretion. A qualitative analysis of the sample should be carried out in each cycle for characterization. The test was carried out for 56 days, with measurements every 15 days.

After the end of the cycles, the sample was washed in a 10% stopper chloride solution to remove excess sodium or magnesium sulfides. Afterward, the sample was washed under running water. A new drying is carried out in the oven, weighing the sample mass, sieving the material, and determining material loss.

The effect of sulfates and counting of the number of affected particles is observed through a qualitative examination. The percentage gives the result by weight of each fraction of sample, which after the test cycles, have a diameter smaller than initially tested, determination of the weighted mean of calculation in the foundation of the percentage of loss of each fraction, based on the granulometry of the sample, and the number of particles larger than 19mm that suffered the action of sulfates and how they behaved (disintegration splitting crushing, breaking, lamination, etc.).

3.3 BEHAVIOR UNDER HYDRAULIC EFFORTS

To evaluate the use of C&DW samples in the face of water abrasion, a non-standard test was performed using a reservoir and applying a varying water flow for one hour and a continuous water flow for two hours. All mass determinations of the assay were performed with samples dried in an oven with a temperature of 105ºC.

Through this non-standard test, we sought to obtain the release of C&DW according to water flows over time, measuring the mass of loose solids due to the abrasion of water on the C&DW. This analysis will be from the point of view of the aggregate.

The samples were dried in the oven to determine the total dry mass of each sample. Later, in separate receptacles, each sample was immersed in water for more than 24 hours to obtain the saturation of each particle in the sample.

After saturation, the sample was placed in the storage reservoir containing and filtering the water. Any particle that detaches can be collected by sieve #200, located at the bottom of the reservoir. This filter reservoir was developed for this research, see Figure 33.

The flows and dry masses of the loose particles were collected according to defined time intervals.

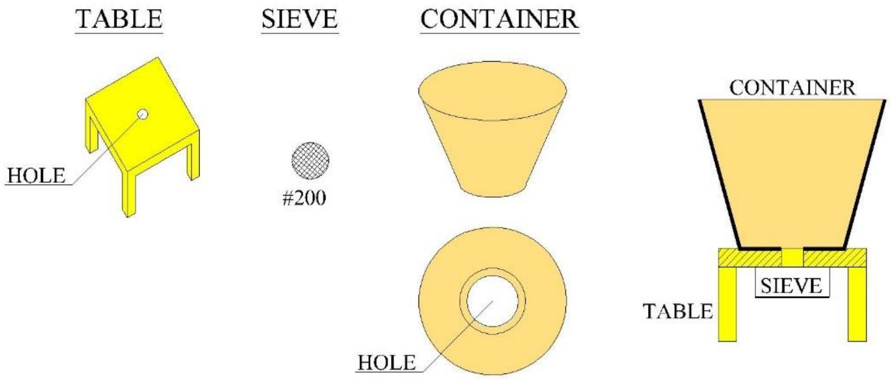


Figure 33. Filter reservoir.

Figure 34. Saturation of the samples.

Figure 35. Performed test.

3.4 ECONOMIC ASSESSMENT

To assess the cost of substituting rocks for C&DW in gabion filling, research was carried out to obtain contacts of recycling plants and quarries located in the metropolitan area of the city of São Paulo. The chosen recycling plants were affiliated with ABRECON (Brazilian Association of Recycling Plants). Only four sell C&DW with the necessary characteristics for gabions´ filling among the seven recycling plants found, as shown in Table 14. The distance between each recycling plant and a construction work (followed described) placed in the East Side of the city was another critical cost assessment criterion. It is very true that the transportation costs are significantly influenced by the distance between the recycling plant and its final destination.

Table 14
C&DW recycling plants relation in metropolitan area of the city of São Paulo.

Material	Company	City location	Distance (km)
C&DW	"I"	Itaquaquecetuba/ São Paulo	44.8
	"L"	Santo André/ São Paulo	18.6
	"P"	Santana do Parnaiba/ São Paulo	10.7
	"R"	São Paulo/ São Paulo	25.6
Natural resource	"I"	Itaquaquecetuba/ São Paulo	51.7
	"L"	Santana do Parnaiba/ São Paulo	37.7
	"P"	São Paulo/ São Paulo	25.6
	"R"	São Paulo/ São Paulo	30.2

For the economic assessment, a construction work, placed on the city's Eastside, was considered. The construction work consists of renovating the lining of an important river in the region. The river's channel was built using gabions that slipped in four places because of unexpected rains. The river is at Jacu-Pessego Avenue, an essential freeway to São Paulo's downtown from East Zone. Figures 36 to 39 present each local. The construction work was built by Progredior Engineering and, the design was developed by Geoconceito Geotechnical Consulting in 2021.

Figure 36. Site #1 – Just after gabions have taken failure

Figure 37. Site #2 – Just after gabions have taken failure

Figure 38. Site #3 – Just after gabions have taken failure

Figure 39. Site #4 – Just after gabions have taken failure

According to the design, the technical solution would be assembled using different gabions: basket gabions, sack gabions, and mattress gabions. The basket gabions were designed for retaining the riverbanks, the sack and the mattress gabions were used for foundation reinforcement. Driven wood piles were also used for the foundation. The retaining walls had an average height of 3.5m, and about 80m of the riverbanks were renewed in all. At some sites, the excavation slopes were stabilized by soil nailing technique to keep safety conditions for gabions assembling. The figures below bring illustrative design sections and photos taken during the assembling works.

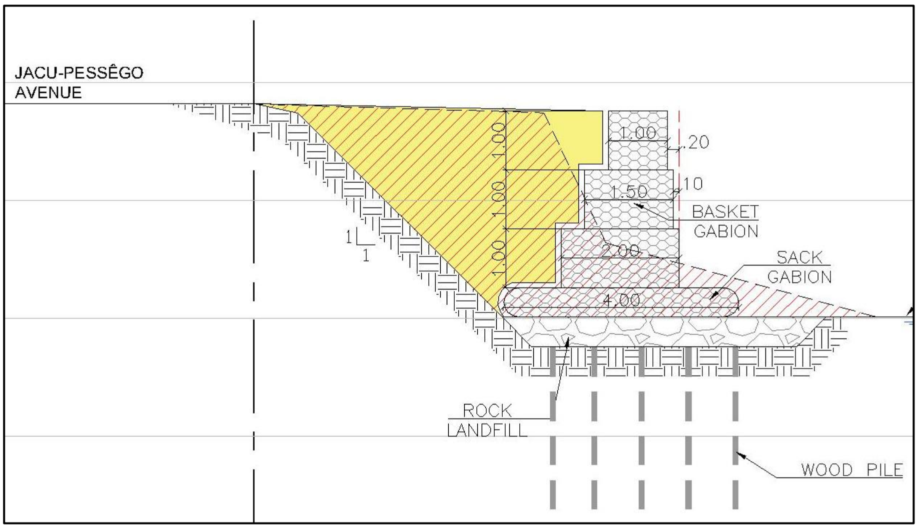


Figure 40. Illustrative design section – site#1

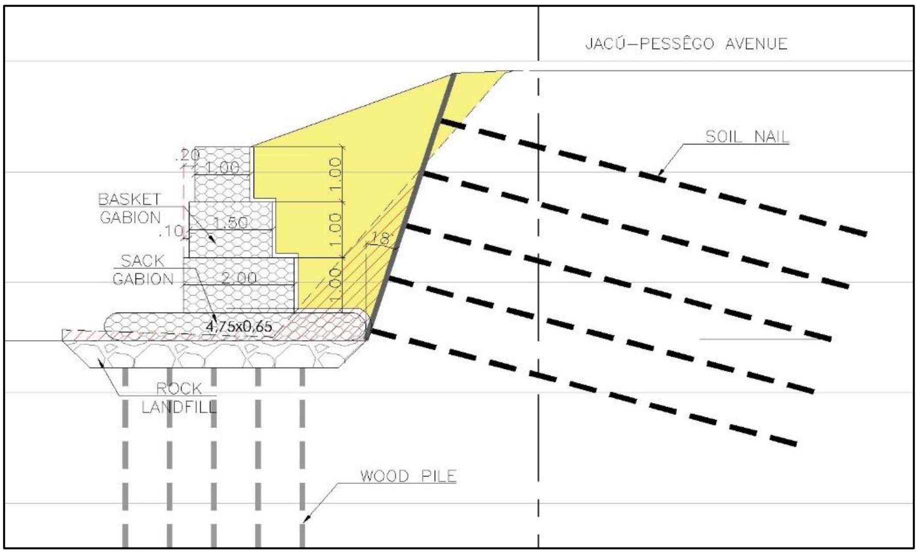


Figure 41. Illustrative design section – sites 2, 3 and 4.

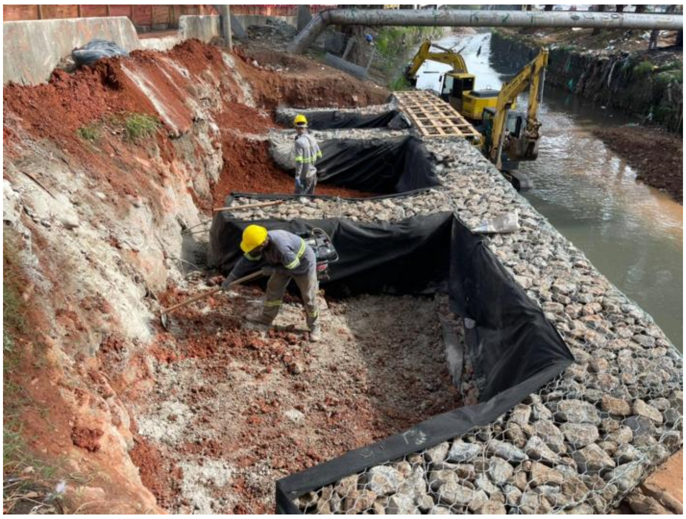


Figure 42. Execution of the compacted landfill behind the retaining wall.

Figure 43. Use of the riverbed as a mobility route for equipment.

Figure 44. Assembly of gabions.

Figure 45. Gabions being filled with rocks

Figure 46. Sites 2 and 3 after gabions assembling.

Figure 47. Site #3 after gabions assembling.

Figure 48. Site #4 after gabions assembling

The table 15 below brings the total amount of each material used during the works.

Table 15

C&DW specific weight

DESCRIPTION	UNIT	TOTAL QUANTITIES
Sack gabion (4m x 0.65m)	**unit**	**106**
Basket gabion	**m^2**	**366**
Filling material (rock)	**m^3**	**436**
Excavation	m^3	1,085
Compacted landfill	m^3	788
Wood piles (Ø0.3m Length= 6m)	m	2,946
Soil nail (Steel bar CA-50 Ø0.016m Length= 8m)	m	2,520

4 RESULTS AND DISCUSSIONS

The obtained data for this research are following shown:

4.1 SPECIFIC WEIGHT

Tables 16 to 17 present the weight-specific mass for C&DW and rock specimens. For each specimen, these values were obtained in different conditions: a) natural moisture content, b) dried in the oven, and c) saturated.

Table 16
C&DW specific weight

Sample	Specific weight (C&DW) (kN/m³)	Dry Specific weight (C&DW) (kN/m³)	Saturated Specific weight (C&DW) (kN/m³)
1	19.27	19.08	19.68
2	19.93	19.82	20.37
3	19.14	19.00	18.59
Average	**19.44**	**19.30**	**19.55**
Sd	**0.42**	**0.46**	**0.90**
Cv (%)	**2%**	**2%**	**5%**

Table 17
Rock specific weight

Sample	Specific weight (Rock) (kN/m³)	Dry Specific weight (Rock) (kN/m³)	Saturated Specific weight (Rock) (kN/m³)
1	24.89	24.86	25.09
2	25.18	25.18	23.46
3	23.18	23.17	25.57
Average	**24.42**	**24.40**	24.71
Sd	**1.08**	**1.08**	1.11
Cv (%)	**4%**	**4%**	4%

As presented in Tables 16 to 17, as known, the rock specimen presented higher average values of specific weight considering any studied condition (natural moisture content, dried or saturated). The average specific weight for C&DW remained between 19.30kN/m³ and 19.55kN/m³, meaning a 1.3% variation. This way, it can be figured out that studied conditions do not influence the obtained specific weight values, pointing out a low absorption characteristic. The low standard deviations points for the specimen homogeneity. The same phenomena can be stated for the rock specimen. The obtained values, such as for C&DW or rock specimen, were within those Camelo (2019) found.

4.2 ABSORPTION

Absorption tests were performed as required by Brazilian Technical Standards; the values are shown in the following table.

Table 18
Absorption values for C&DW and Rock specimen

Sample	Specimen	Absorption	Sample	Specimen	Absorption
C&DW	1	1.86	Rock	4	0.31
	2	4.69		5	0.18
	3	0.96		6	0.22
Average		**2.50**	Average		**0.24**
sd		**1.95**	sd		**0.07**
Cv (%)		**77.83**	Cv (%)		**29.66**

The C&DW specimen showed 2.5% as absorption average value (sd=1.95, cv=77.8%). The average value for rock specimen was 0.24% (sd=0.07; cv=29.66%). As expected, the rock specimen pointed out for a lower absorption value. The absorption values found for rock and C&DW specimen were closer to those found by Sbrighi Neto (2005) and Camelo (2019) respectively. It must be highlighted that the absorption values obtained for the specimen are under the requirements established by Brazilian Technical Standards.

4.3 SHAPE INDEX

The shape index values for each specimen are presented in the following table:

Table 19
Shape index values for C&DW and rock specimen

Sample	Mean length (mm) a	Mean thickness (mm) b	Relation b/a	Index shape
C&DW	120.01	60.84	0.51	**1.97**
Rock specimen	118.05	62.83	0.53	**1.88**

The shape index values for each specimen were: 1.97 (C&DW) and 1.88 (rock). These values address, according to Brazilian Technical Standard 5564/2021, for cubic shape classification. It must be stated that the shape index is one of the requirements established by

Brazilian Technical Standards to choose materials for gabions filling. This way, both samples are under the requirements of Department of Highways of the State of São Paulo (2006).

4.4 LOS ANGELES ABRASION TEST

The following table bring the values obtained by the Los Angeles abrasion tests performed:

Table 20
Los Angeles abrasion index determination

Material	Sieve opening (mm)			Specification		Mass (g)				Abrasion index (%)
	past thru	retain	quantity (g)	graduation	number of spheres	spheres	Initial	Final	loss	
C&DW	75	63	5,000	"E"	12	4,984	10,042	6,146	3,896	**38.8**
	63	50	5,042							
Rock specimen	75	63	5,022	"E"	12	4,986	10,022	8,882	1,140	**11.4**
	63	50	5,000							

As shown in Table 20, the Los Angeles abrasion index for C&DW and rock specimen were 38.8 and 11.4%, respectively. The obtained value for C&DW addresses it to the Department of Highways of the State of São Paulo (2006) requirements for gabion filling, lower than 50%. As expected, the C&DW presented much abrasion than the rock sample. Hansen and Narud (1983) stated that the C&DW abrasion index could reach 50% higher than rocks. However, the authors also point out that, for high-strength concrete wastes, the abrasion index trends to be closer to rocks. The obtained abrasion index for C&DW turns it reliable for paving uses (Brazilian Association of Technical Standards ABNT/NBR 5564-2021).

4.5 DURABILITY TEST

Once the studied materials are being assessed for gabions filling purposes (and considering that gabion is much used for river coating), durability tests using sodium sulfate were performed. The following figures present the tests performed and the obtained data. The tests were carried out straightly under the ASTM C88 (2018) requirements.

Figure 49. Natural stone container with sodium sulfate solution.

Figure 50. C&DW container with sodium sulfate solution.

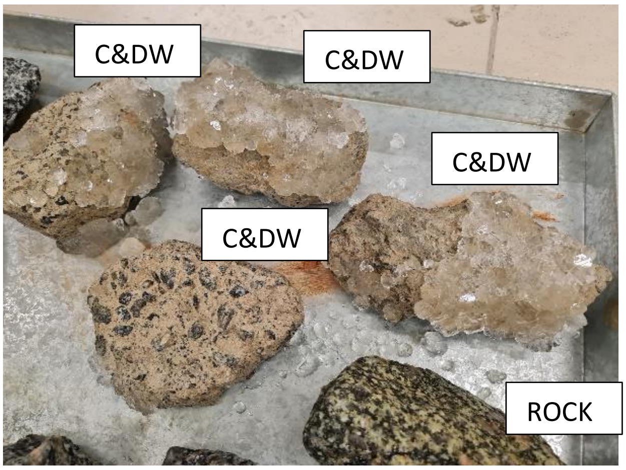


Figure 51. After the first immersion cycle, crystals adhered to the samples.

Figure 52. Presence of desegregation on the waste surface after 31 days of immersion (3cycles).

Figure 53. Presence of laminations on the waste surface after 31 days of immersion (3cycles).

Figure 54. Desegregation during immersion.

Figure 55. The breakage of one of the sample elements.

Figure 56 shows the obtained data for both specimens.

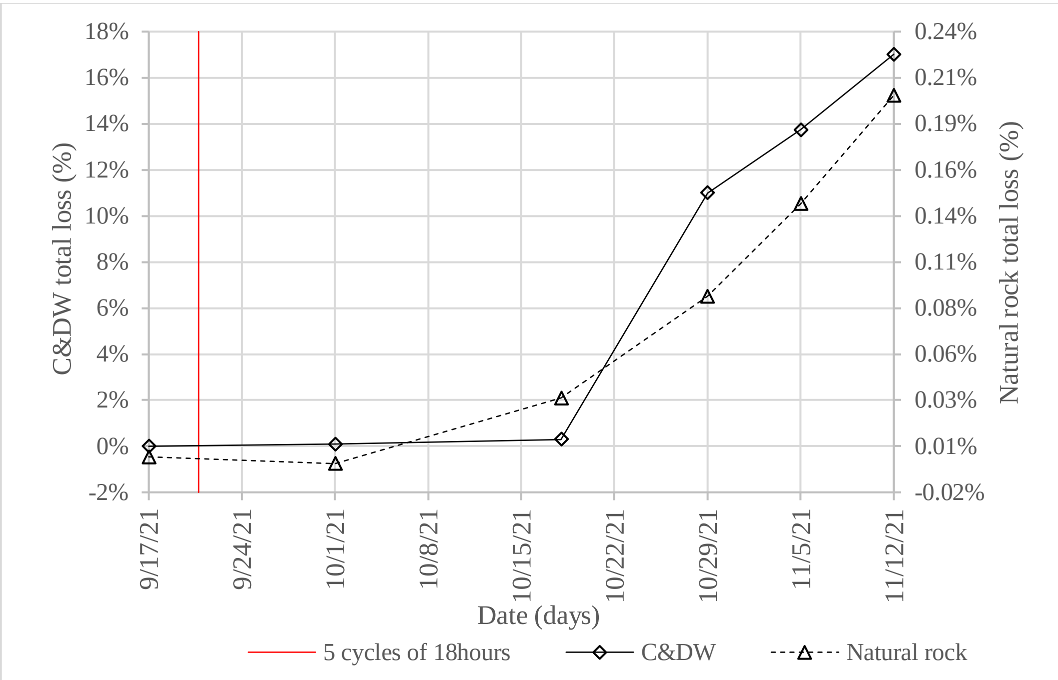


Figure 56. Results of the durability test.

The data shown in Figure 56 was possible to figure out that the C&DW wastes were more susceptible to the sodium sulfate attack than the rock sample. Besides C&DW degradation values reaching 17%, the rock samples were kept under 0.2%. The degradation percentage obtained for the C&DW sample can be addressed to the requirements established by the Brazilian National Department of Highways (1994) requirements for gabion filling, turning the

C&DW on a reliable material for it. This requirement stated that the filling material must reach up to 20% of abrasion.

4.6 WATER ABRASION

As already stated, sacks, mattress and basket gabions are often used for river coatings; this way, the abrasive effect caused by water flux over then consists of an issue for studying. So, aiming to figure out how the water flux can affect the filling materials, the researchers developed an experimental procedure. It must be highlighted that there were no technical standards about similar procedures for obtaining the abrasive water effect over gabions' filling materials. The test procedures details were stated in the material and methods chapter. The test was run only for C&DW samples. The obtained data are shown in the Figures below.

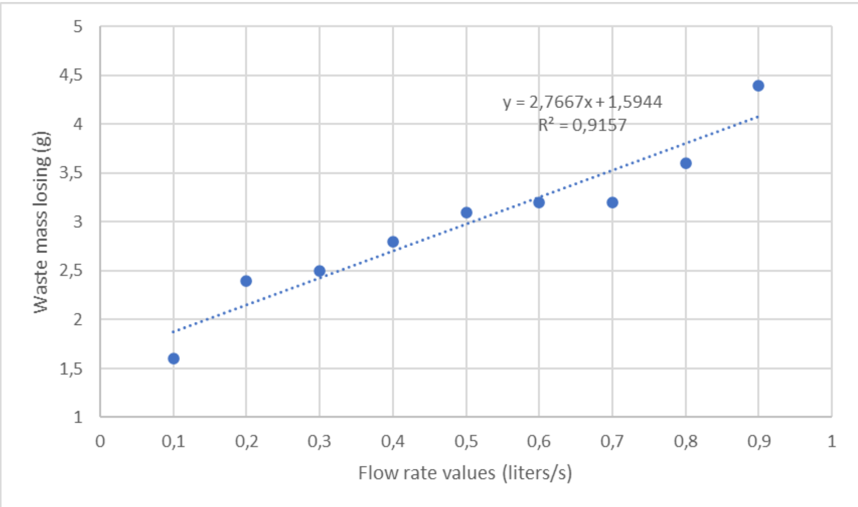


Figure 57. C&DW mass losing by flow rates increasing.

As led in Figure 64, a good relationship between mass loss and water flow rate can be pointed. During the whole performed test, the C&DW sample lost 4.5g, corresponding to 0.05% of its initial weight. The C&DW wastes were also assessed, considering different water flow rates. This procedure had as goal simulate other flow conditions that the C&DW wastes can be submitted. The following figures come out with the effect of 0.5, 1.0, 1.3, and 2.0m/s speed flux rates over the C&DW.

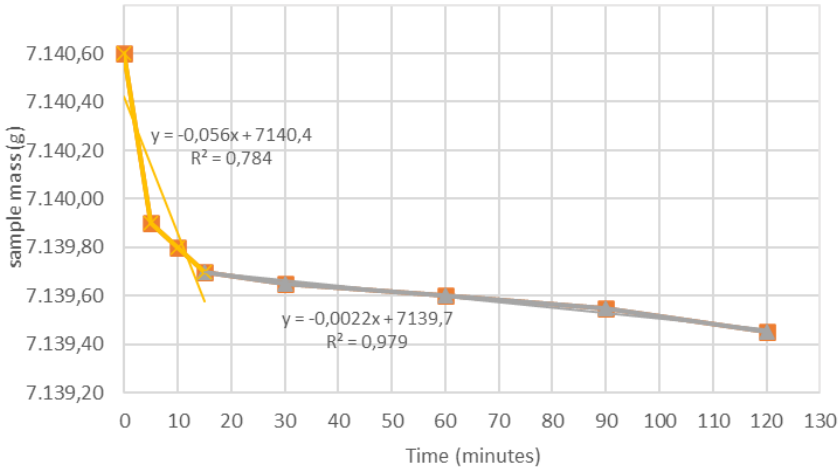


Figure 58. Relationship between time and material loss over a mean water speed of 0.5m/s.

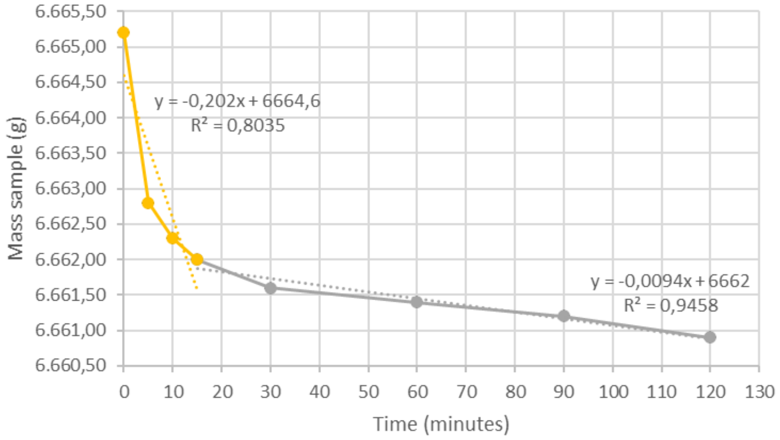


Figure 59. Relationship between time and material loss over a mean water speed of 1.0m/s.

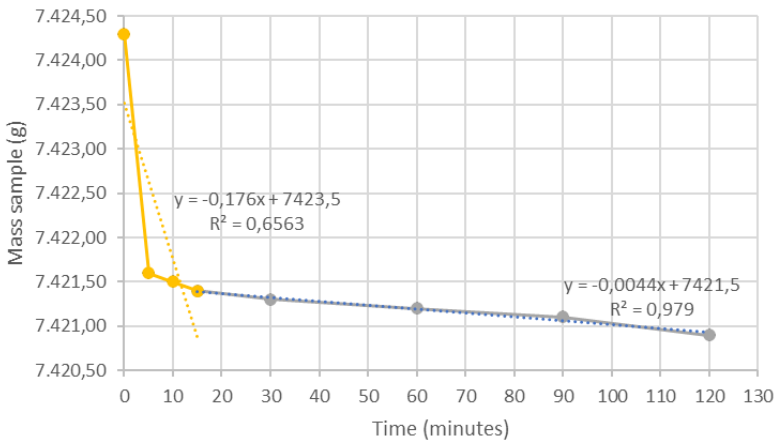


Figure 60. Relationship between time and material loss over a mean water speed of 1.3m/s.

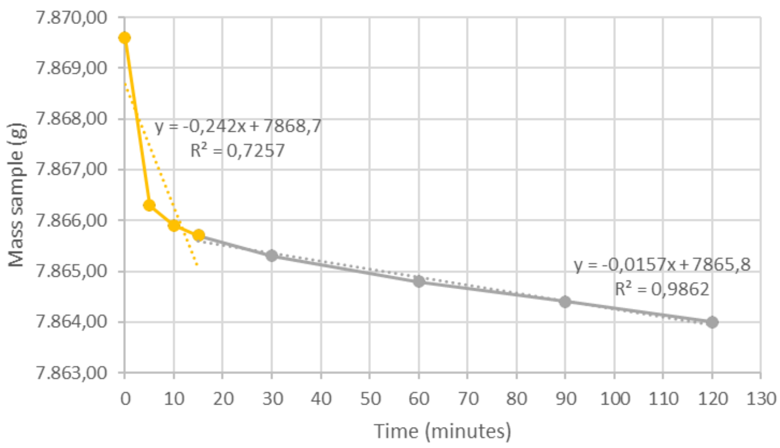


Figure 61. Relationship between time and material loss over a mean water speed of 2.0m/s.

Analyzing the figures, two different correlations can be noticed. The first one describes the water flow rate effect over the C&DW up to 15 minutes and the other up to the end of the test performed. As a matter of fact, until 15 minutes, the C&DW had lost much faster mass fitting to a linear trend. After the first 15 minutes, the C&DW continued to lose its mass; however, in less intensity. The figured out-trend had fitted to a linear after 15 minutes of water flow. Although the C&DW mass loss had presented a decrease, it had not leveled off, pointing out a constant mass loss by the time. The figure below brings a comparison between the gotten curves.

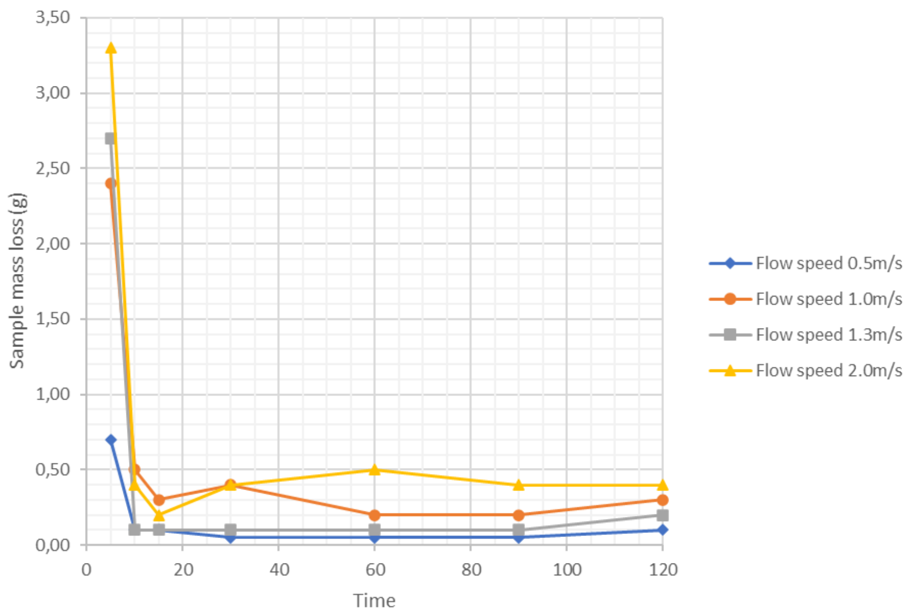


Figure 62. Comparison between the results obtained.

The water abrasion tests performed show that the water flux rate versus mass loss can be settled in a linear trend by time. On the other hand, this behavior points to a non-desirable behavior for a gabion filling material. Although the C&DW wastes have met the requirements of the technical standards up to now, the found phenomena can not fit those. So, a situation can be realized. The constant mass loss of the filling material (C&DW) can lead to excessive displacements into the gabions, addressing the whole structure to a further slip failure. However, Camelo (2019) stated that C&DW could be reliable for gabions filling concerning retaining wall use. This way, considering the whole picture, the performed tests had not excluded the possibility of C&DW using for hydraulic works; as a matter of fact, the obtained data addresses a need for a concrete coating over the gabion filled with C&DW, aiming to avoid the contact between the water and the filling material. The use of the C&DW wastes itself under hydraulic efforts can be taken as reliable; however, a layer of mortar must be projected over the external gabion's superficies.

4.7 ECONOMIC ASSESSMENT

The purchase costs for rock and C&DW acquisition were asked in different recycling plants and quarries near São Paulo. The obtained values are shown in Table 21. The presented purchasing values include, further than material acquisition, the delivering costs.

Table 21
C&DW and rock materials trading costs.

Material	Recycling plant/quarry	Distance (km)	Cost US$/t*	Average cost (US$)	Sd	Cv (%)
C&DW	I	44.8	0.23	0.25	0.04	18.1
	L	18.6	0.22			
	P	10.7	0.32			
	R	25.6	0.24			
Rock	I	51.7	0.30	0.30	0.02	8.5
	L	37.7	0.30			
	P	25.6	0.32			
	R	30.2	0.26			

* Delivery included - note: Dollar exchange on 12/01/2022 – US$1.00 = R$ 5.563

As shown in Table 21, the C&DW has presented a lower average cost than the rock, pointing to a 16.7% difference in the average costs. The C&DW costs also showed more variation between the asked plants than the rock, and it can be noticed comparing the variation coefficients calculated (cv). Even though the C&DW purchase costs can figure mores attractive, the difference between it and the rock costs was not so far, and lower than those noticed by Paschoalin Filho et al. (2018), about 40%. As a matter of fact, the low difference between both purchase costs can turn not economical viable the C&DW acquisition by the building companies. However, it must be highlighted that the purchasing costs usually show variation according to the market situation and material availability. At the moment the costs were obtained, rocks and natural aggregates were more available for buying than C&DW, addressed mainly by the low building construction rates. In this way, as noticed by Paschoalin Filho (2018) once the building activities rates get higher, the difference between C&DW and natural raw material purchasing costs tends to increase.

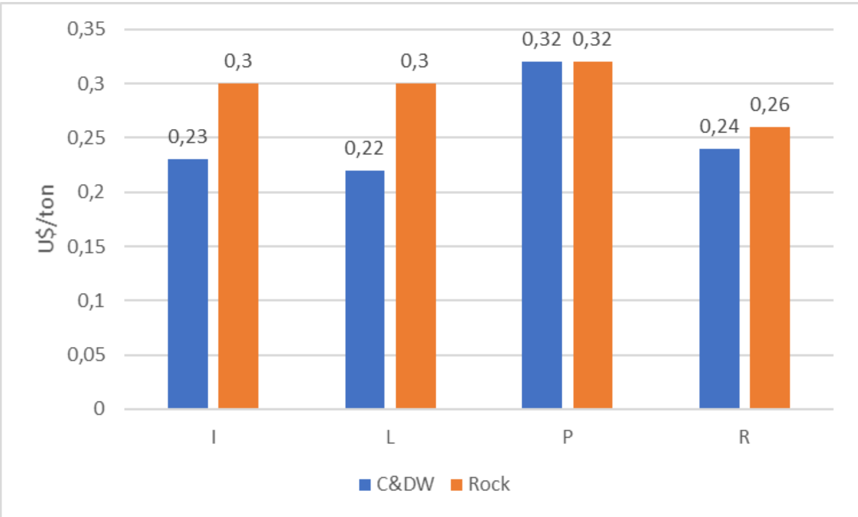


Figure 63. Purchasing costs comparison between the recycling plants/quarries.

As stated before, a real construction work placed at East Zone of São Paulo was framed for economic assessment performing. The construction work was built using different kinds of gabions. For the filling, rocks were used in the gabions. As noticed by design, all gabions filling an amount of 436m^3 were used. The costs for gabions coating with projected concrete were also taken into consideration. This way, three conditions were analyzed:

- Gabions filled with rocks;
- Gabions filled with C&DW;
- Projected mortar over gabions filled with C&DW.

The costs for mortar projecting were based on the standard cost's basis of the Department of Roads and Roading of the State of São Paulo, the reference year 2021. According to item nº 27.11.10 "Mortar - Cement and sand, Dash 1:3 Thickness 0.02m," the cost is US$9.56 per square meter of surface. The estimated costs were placed in the tables below.

Table 22
Costs applied for fill quantities indicated in the study case.

Material	Recycling plant/ quarry	Distance (km)	Cost US$/t*	Average cost (US$)	Volume - Study case m³	Volume - Study case t	Material + Transport cost (US$)	Mortar cost (US$)	Total cost (US$)	Average cost (US$)	Cost per meter of solution	Average cost (US$)
C&DW + Mortar	I	18.7	0.23	0.25	436	847.58	3645.46	3098.54	6744.00	9557.77	84.30	119.47
	L	20.1	0.22				3748.02		6846.56		85.58	
	P	26.9	0.32				7296.00		10394.54		129.93	
	R	54.8	0.24				11147.42		14245.96		178.07	
Rock	I	18.7	0.3	0.30	436	1064.71	5973.03	-	5973.03	12922.41	74.66	161.53
	L	35.9	0.3				11466.95		11466.95		143.34	
	P	56	0.32				19079.64		19079.64		238.50	
	R	54.8	0.26				15170.02		15170.02		189.63	

* Delivery included - note: Dollar exchange on 12/01/2022 – US$1.00 = R$ 5.563

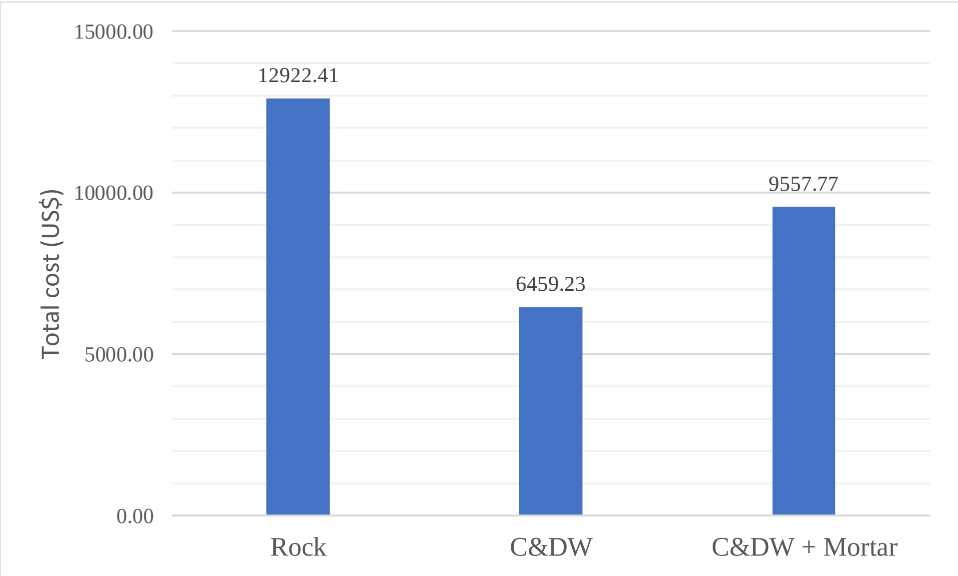


Figure 64. Building costs comparison between the three studied situations.

According to figure 64, the economic feasibility of C&DW as filling material comes out. Even taking into consideration the C&DW coated with mortar, the difference between building costs between this and the rock filling has reached 26%. Balancing the building costs of C&DW and rock as filling material, the difference between them has reached 50%.

5. CONCLUSION

Scientific research concerning the development and evaluation of sustainable building materials is essential in inserting the environmental variable in civil construction. However, it is not just in the environmental sphere that research is vital, but in urban planning too. Among the various problems that involve the governance of a municipality, the management of municipal solid waste has a prominent role since it represents a good portion of the city's budget. Without proper collection, transportation, and deposition care, the accumulation of waste can lead to public health problems, floods, flooding, negative visual aspects, and bad smell.

It is noteworthy that for many years in Brazil, uncontrolled landfills were created where there was no distinction of deposited materials, such as inert materials, domestic and hospital waste (discarded from irregular form). With awareness and development, local laws were created and regulations were imposed, resulting in controlled landfills. However, such landfills increasingly require physical spaces for their installation and operation. Thus, the urban planning to be employed has to seek sustainable alternatives to give due directly to the solid waste generated.

Since civil construction waste represents a significant portion of municipal solid waste generation, as some authors correspond to 50 - 70% of the volume generated, its correct referral is of paramount importance. However, this type of waste has a high potential for reuse from recycling materials.

As noted, the economic gains generated by the exchange and application of C&DW in filling gabions in urban rivers can cause savings in the public budget, reducing spending on transportation and deposition of waste and purchase of natural stones from standing deposits. From an environmental point of view, its use reduces the extraction of natural resources, reduces the burning of fossil fuels used by extraction and transport equipment, and reduces the need for landfill deposition of inert material.

Therefore, the analyzes proposed in this research attest to the feasibility of replacing natural rockfill with class A construction waste, of the same granulometry, for filling gabions in civil works. However, the C&DW must receive a surface coating to protect against continuous water flow. Through the tests carried out of abrasion by water, it was possible to verify that the degradation by water flow along time represents a loss volume that could carry on in problems in the future because of deformations and ruptures of the structures. As demonstrated in terms of technical standards, the use of C&DW as filling material of the gabion met all requirements.

The physical characterization tests of C&DW found that the residues have stone shapes with dimensions similar to natural rock since both crushing uses the same type of mechanical crusher. From the point of view of specific mass and water absorption, it was determined that C&DW has a lower weight than rock. By the sulfate assay, it was found that both C&DW and rock are possible to attack sodium sulfate, where the trips obtained are within the limits accepted by technical specification. In relation to Los Angeles abrasion, an acceptable wear and tear was determined for C&DW within the limit accepted by the current Brazilian Technical Standard.

Due to physical and economic issues to perform the tests on time, it is emphasized that the study carried out has the limitation about the behavior of C&DW towards critical velocity that can generate drag force, resulting in a displacement of fillers inside the gabion. It would be necessary to conduct a full-scale test to evaluate this behavior properly.

It is suggested for further research the approach to seek more information regarding the wear of C&DW in the face of water flow, applying scale models in hydraulic laboratories. Such research should seek to determine the behavior of waste for speeds greater than 2m/s and metal screen/fill set. It is emphasized that the trials presented in this research were based only on the behavior of the filling without the proper confinement generated by gabion.

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