Challenge Journal of
CONCRETE RESEARCH LETTERS

Vol.14 No.4 (2023)

absorption aerated concrete artificial neural network

compressive strength concrete corrosion

cracking curing ductility durability energy

absorption ferrocement flexural strength

fly ash fracture mechanics mechanical properties

mortar nanoparticle reinforced concrete

self- compacting concrete steam curing

strengthening superplasticizer tensile strength

workability waste disposal water a ption

ISSN 2548-0928

TULPAR
ACADEMIC PUBLISHING

EDITOR IN CHIEF

Prof. Dr. Mohamed Abdelkader ISMAIL	*Miami College of Henan University, China*

EDITORIAL BOARD

Prof. Dr. Ashraf Ragab MOHAMED	*Alexandria University, Egypt*
Prof. Dr. Ayman NASSIF	*University of Portsmouth, United Kingdom*
Prof. Dr. Gamal Elsayed ABDELAZIZ	*Benha University, Egypt*
Prof. Dr. Hamidah Mohd SAMAN	*Universiti Teknologi Mara, Malaysia*
Prof. Dr. Han Seung LEE	*Hanyang University, Republic of Korea*
Prof. Dr. Zubair AHMED	*Mehran University, Pakistan*
Prof. Dr. Jiwei CAI	*Henan University, China*
Prof. Dr. Jahangir MIRZA	*Hydro-Québec Research Institute, Canada*
Prof. Dr. Ahmet Ferhat BİNGÖL	*Atatürk University, Türkiye*
Assoc. Prof. Dr. Meral OLTULU	*Atatürk University, Türkiye*
Assoc. Prof. Dr. Saleh Omar BAMAGA	*University of Bisha, Saudi Arabia*
Assoc. Prof. Dr. Mohammed Seddik MEDDAH	*Sultan Qaboos University, Oman*
Assoc. Prof. Dr. Brabha NAGARATNAM	*Northumbria University, United Kingdom*
Dr. Aamer Rafique BHUTTA	*Aramco, Saudi Arabia*
Dr. Khairunisa MUTHUSAMY	*Universiti Malaysia Pahang, Malaysia*
Dr. Mahmoud SAYED AHMED	*Ryerson University, Canada*
Dr. Jitendra Kumar SINGH	*Hanyang University, Republic of Korea*
Dr. Türkay KOTAN	*Erzurum Technical University, Türkiye*
Dr. Ali KEYVANFAR	*Kennesaw State University, United States*
Dr. Arezou SHAFAGHAT	*Kennesaw State University, United States*

E-mail: *cjcrl@challengejournal.com*

Web page: *cjcrl.challengejournal.com*

TULPAR Academic Publishing
www.tulparpublishing.com

Challenge Journal of Concrete Research Letters

CONTENTS

Research Articles

Reviews

TULPAR
ACADEMIC PUBLISHING

CHALLENGE JOURNAL OF CONCRETE RESEARCH LETTERS 14 (4) (2023) 96–106

Challenge Journal of Concrete Research Letters

Research Article

Optimization of reinforced concrete beam using hybrid algorithms with multi-objective function as CO_2 emission and cost

Muhammed Çoşut [a], Gebrail Bekdaş [a], Sinan Melih Nigdeli [a],*

[a] *Department of Civil Enginering, İstanbul University-Cerrahpaşa, 34320 İstanbul, Türkiye*

ABSTRACT

In this study, algorithms with two objective functions are defined considering the TS500 (2000) (Reinforced concrete structures design and construction rules) and TBDY (2018) (Turkey Building Earthquake Regulation) standards for rectangular beam design. These objective functions were determined as CO_2 emission and cost. Optimizations were performed in MATLAB program using the Hybrid Algorithm of Teaching-Learning Based Optimization and Jaya Algorithm. In the case of using two objective functions, cases were created by multiplying the coefficient values found in the objective function according to the formula with the cost and CO_2 emission values at different rates in order to prevent CO_2 emission which is one of the biggest problems for the world. In the objective function, each rate used for CO_2 and cost is implemented in a manner that increases or diminishes the impact of these values. In this way, comparisons were made between the cross-section dimensions to be formed according to not only impact rates but also the reinforcement area to be used, the CO_2 emission and cost values that will arise as a result of these. Impact rates are related to cost and CO_2 rate in the objective function, and the total rate is chosen as 1. Impact rates for cost are chosen as 0.1, 0.3 along with 0.5, and comparisons between the results are checked. In addition, recyclable and non-recyclable steel with different properties were used in separate analyses and the values were compared. Since the CO_2 rate released by the non-recyclable steel is very high compared to the recyclable steel, the results show that the CO_2 emission value is higher and this causes the objective function value to increase.

ARTICLE INFO

Article history:
Received 28 June 2023
Revised 23 July 2023
Accepted 4 August 2023

Keywords:
Multi-objective optimization
CO_2 emission
Cost optimization
Hybrid algorithm
Beam design

1. Introduction

Most of the engineering works that have been done and completed in the past are designed by taking into account the conditions such as strength and service life. However, in addition to strength and other required properties, sustainability studies have begun to be considered an important design condition for the protection of nature. One of the biggest reasons for the adoption of sustainable designs is the increase in the amount of annual CO_2 emissions. While the annual CO_2 emission was around 6 billion tons worldwide before the 1950s, today this value is measured as more than 38 billion tons (URL-1 2023) by increasing rapidly. Therefore, the CO_2 emission reduction process is carried out by different studies in different engineering fields.

When the construction sector and the buildings are taken into account, it is explained in the reports that according to the data explained above, approximately 38% of the CO_2 rate is released worldwide. Moreover, that 5% CO_2 is released by cement is computed by IPCC 2006 standard (Kara et al. 2018). For this reason, significant studies are carried out in terms of both reducing CO_2 emissions and reducing costs to realize the most appropriate and efficient design in the construction industry. These studies can be done in different ways. To exemplify, these are the use of materials that are less harmful to the environment and have high durability by increas-

---

* *Corresponding author.* Tel.: +90-212-473-7070 ; Fax: +90-212-889-1887 ; E-mail address: melihnig@iuc.edu.tr (S. M. Nigdeli)

ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2023.04.001

ing the variety of materials that can be used (Kayabekir et al. 2020; Li 2011; Habert and Roussel 2009), the availability of sufficient cross-section dimensions according to the force affecting the necessary construction element and the standard of the country where it is located, the selection of more effective structural systems and the recyclability of the materials used in the construction. As result of such studies, it contributes to the prevention of global climate change, reducing the carbon footprint of buildings, efficient use of resources and increasing efficiency in the project process. In order to control such as emissions and cost, metaheuristic algorithms have been used in many areas to reach pertinent design, and the objective function of a design may contain more than one variable. Cakiroglu et al. (2021a) have conducted to find CO_2 and cost optimization for concrete-filled steel tubular columns. In addition, Cakiroglu et al. have used Harmony Search (HS) (2021b) and Manta Ray Foraging – Jaya Hybrid Optimization (2023a) to accomplish CO_2 emission for concrete-filled steel tubular rectangular stub columns. Cantilever shoulder pile retaining walls which are indispensable to remain steady in the soil have reached optimal design by using a method of data-driven ensemble learning (2023b). Cakiroglu and Bekdaş (2022) have analysed CFST stub columns to find the axial load capacity. In order to display the algorithms how many iterations they could reach the objective function in problem as optimization cost, Çoşut et al. (2023) have utilized the algorithms which are Harmony Search (HS), Differential Evolution Algorithm (DE), Hybrid Algorithm, Flower Pollination Algorithm (FPA), Jaya Algorithm, Teaching- Learning Based Optimization (TLBO). Temür (2021) has generated a Hybrid TLBO algorithm for the optimum design of cantilever retaining walls under seismic loads. The type of optimization can be different and one of them known as multi-objective optimization has been used many times in the optimization of beams. Aydoğdu (2017) has performed multi-objective optimization of cantilever retaining walls in terms of cost and CO_2. Paya- Zaforteza et al. (2009) have optimized reinforced concrete frames by using simulated annealing and Spanish Code as multi-objective functions related to CO_2 emission and cost. Leps and Sejnoha (2003) have used genetic algorithms to reach the optimum total cost for steel-reinforced concrete structures. Camp and Assadollahi (2013) used a hybrid algorithm which was a big bang-big crunch algorithm about optimizing CO_2 and cost in the design of reinforced concrete footings. Kripka and de Medeiros (2012) studied the cross-sectional optimization of reinforced concrete columns at the firstly cost, after that, they utilized Life Cycle assessment to reach the environmental effect. Therefore, they have tried to decrease the amount of CO_2 according to cost [10]. Reinforced concrete structures which were beams have been optimized by Afshari et al. (2019), and also, they have focused on the approaches of multi-objective optimization. Yeo et al. (2015) studied to generate a design which was about reinforced concrete structures to minimize CO_2 emission. Joyner et al. (2021) have optimized the buildings according to resilience-based seismic design, and life span performance along with conditional performance have been controlled. Yücel et al. (2021) have optimized rectangular beams in terms of CO_2 emission to design an environmentally friendly structure element; however, Abubakar et al. (2021) have used genetic algorithms to optimize the design of rectangular beams. Also, machine learning techniques are a new trend in the prediction of optimum design parameters without rerunning the iterative optimization process (Ocak et al. 2013, Aydın et al. 2013).

In this study, the optimization of the rectangular reinforced concrete beam in terms of both CO_2 emission and cost was carried out with the hybrid algorithm created by the synthesis of metaheuristic algorithms using the MATLAB program. Since two objective functions were defined in the optimization process, their sum was adjusted in certain proportions, the dimensions of the rectangular beam, the required reinforcement area, the cost and the released CO_2 values were recorded and the results were compared according to the determined rate values. In addition, the differences in the variable and objective function that occur when steels with different properties are used were compared.

2. Features and Design of the Beam

Many countries have developed their own building design and construction regulations over time. These standards have evolved and developed based on a certain accumulation of knowledge, laboratory studies, and experience with destructive natural disasters. As a result, designs for resilient systems can be developed against unwanted and destructive situations.

In structural design, beams are widely used as building elements. These elements not only perform well against bending moments and shear forces but also transfer loads from slabs to columns. Beams can be designed in various shapes, such as T-shaped, I-shaped, and L-shaped. Depending on the desired design, there may be some minor changes in the calculation formulas. Additionally, the span length can vary depending on the desired design, while keeping within certain limits (Doğangün 2019).

In this study, the design of a rectangular beam (Fig. 1) is carried out by considering the TS 500 (2000) and TBDY (2018) regulations, and the necessary equations for the design are presented.

In the following equations, f_{ctd} is the tensile strength of concrete, f_{ck} is the characteristic strength of concrete, f_{cd} is the design strength of concrete, f_{yk} is the characteristic yield strength of steel, f_{yd} is the design yield strength of steel. The depth of the compression block (Eq. 2) is calculated based on the effective height of the beam (d), the load affecting the beam, the span, and the concrete grade used. As a consequence, the reinforcement area can be found in Eq. (3).

$$f_{ctd} = 0.35 \times \frac{\sqrt{f_{ck}}}{1.50}, \quad f_{cd} = \frac{f_{ck}}{1.50}, \quad f_{yd} = \frac{f_{yk}}{1.15} \tag{1}$$

$$a = d \pm \sqrt{d^2 - \frac{2 \times M_d}{0.85 \times f_{cd} \times b}} \tag{2}$$

$$A_s = \frac{M_d}{f_{yd} \times \left(d - \frac{a}{2}\right)} \tag{3}$$

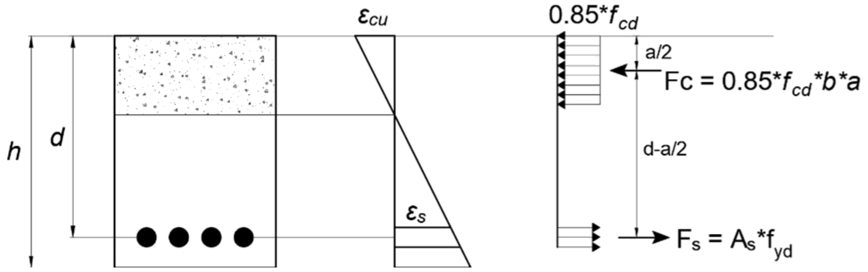

Fig. 1. Under loading for RC beam.

The adequacy of a beam in resisting shear forces under loading conditions is examined, and accordingly, the required reinforcement area is selected and placed at the necessary distance in compliance with regulations. The shear force value provided by concrete is given in Eq. (4).

$$V_{cr} = 0.8 \times \frac{0.65 \times f_{ctd} \times b \times d}{1000} \tag{4}$$

In certain situations and under specific loads, even if it is calculated that all shear forces of the designed beam are carried by the concrete (V_{cr}), reinforcement calculation and placement should be done according to the minimum requirements of the regulations. This will ensure that the structural element functions effectively under dynamic loads, preventing damage to the system. V changing by loading (Q) is the shear force of system.

$$V_d = V - \frac{Q \times \left(d + \frac{a}{2}\right)}{1000} \tag{5}$$

The stirrups used to resist shear forces are placed at different distances in the wrapping and middle regions (Fig. 2). This is because the beam will be subjected to maximum shear forces at the column-beam joints, and a denser and closer stirrup arrangement is required for the safe transfer of these forces. According to the regulations, the distances between the stirrups to be placed in these two regions are given in Eqs. (6) and (7).

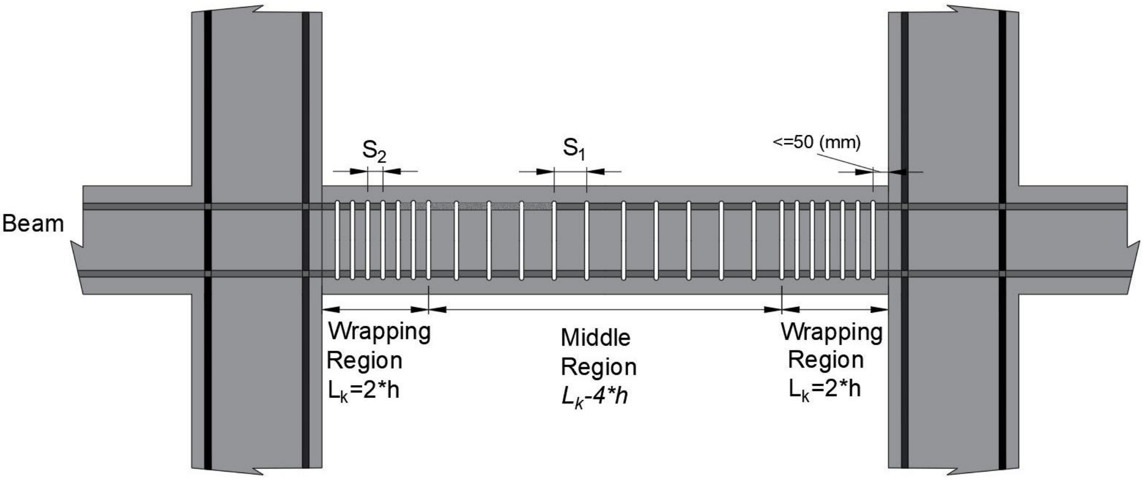

Fig. 2. Layout of the stirrups.

$$\text{middle region} \leq \begin{cases} V_d \leq 3 \times V_{cr} \quad S_1 = \frac{d}{2} \\ V_d > 3 \times V_{cr} \quad S_1 = \frac{d}{4} \\ S_1 > 350\text{ mm} \quad S_1 = 350\text{ mm} \end{cases} \tag{6}$$

$$\text{wrapping region } (S_2) \leq \begin{cases} \frac{h}{2} \\ 8 \times \emptyset\ (\emptyset 8 \text{ or } \emptyset 10) \\ 150\text{ mm} \end{cases} \tag{7}$$

For the concrete to be placed homogeneously between the reinforcements, the horizontal and vertical net distances between the longitudinal reinforcements must be at a certain value. These values are determined by considering the maximum aggregate diameter, which is 22 mm (D), that can be used in the concrete, constant and rebar diameter (Eq. (8)).

$$\text{net distance} \geq \begin{cases} 25 \\ \emptyset\ (\emptyset \geq \emptyset 12) \\ 4 \times \frac{D}{3} \end{cases} \tag{8}$$

3. Metaheuristic Algorithm

The metaheuristic algorithms which are a comprehensive problem-solving method for a variety of problems have been found and developed over time by inspiring natural events (Bekdaş et al. 2021). Flower Pollination Algorithms (FPA) (Yang 2012), Jaya Algorithm (Rao 2016), Teaching-Learning Based Optimization (TLBO) (Rao 2011) and Bat Algorithm (Yang and Gandomi 2014) can be given as examples. These algorithms which are more effective to reach objective functions than traditional methods can be used for finding optimal solutions. Furthermore, various fields employ the algorithms such as engineering, manufacturing, financial risk management, artificial intelligence, machine learning, operation research and management science. All these fields have some goals such as optimizing CO_2 emission, cost along with weight. Thus, engineers should apply the objective function according to the priority of the problem. Objective functions can be generated as single-objective functions, multi-objective functions as well as constraint optimization functions.

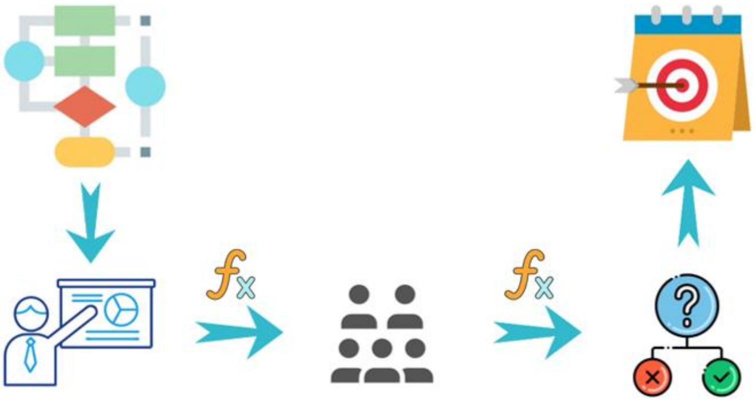

Fig. 3. The metaheuristic algorithm process.

3.1. Hybrid algorithm

Nowadays, there are several metaheuristic algorithms which have different properties like phase number, equations and control parameters. In addition, hybrid algorithms have been developed over time to facilitate the efficient and effective resolution of more complex and comprehensive problems. These algorithms are obtained by combining two or more algorithms, thereby improving optimization performance. The ways to combine metaheuristic algorithms (Khajehzadeh 2016) are sequential hybridization, parallel hybridization and integrative hybridization. In addition, some hybrid algorithms have been combined as TLBO-Jaya (Teaching-Learning Based Optimization- Jaya Algorithm), GAAP (Hybrid Ant Colony-Genetic Algorithm), ACO-GA (Ngatchou et al. 2015) and DE-BBO (Hybrid Differential Evolution-Biography Based Optimization) which can be used for complex problems.

In this study, the TLBO-Jaya hybrid algorithm was used to be completed all requirements. TLBO has two phases which are known as Teaching (Eqs. (9) and (10)) and the Learning phase. All two phases have different equations to reach and compare objective functions. In order to generate a Hybrid Algorithm, equations of the learning phase are removed by equations of Jaya algorithms, which are illustrated in Eq. (11). TF is known as the teaching factor, $X_{i,\text{new}}$ is a new value, $X_{i,j}$ is a candidate solution's value, $X_{i,a}$ and $X_{i,b}$ are chosen randomly, $X_{i,g_{\text{best}}}$ is an objective function's best value, $X_{i,g_{\text{worst}}}$ is an objective function's worst value.

$$TF\ = \text{round}(1 + \text{rand}()) \tag{9}$$

$$X_{i,\text{new}} = X_{i,j} + \text{rand}(\,)\left(X_{i,g_{\text{best}}} - \left|X_{i,j}\right|\right) - (TF)X_{i,\text{mean}}) \tag{10}$$

$$X_{i,\text{new}} \begin{cases} AF_a < AF_b, \quad X_{i,j} + \text{rand}(\,)\left(X_{i,a} - X_{i,b}\right) \\ AF_a > AF_b, \quad X_{i,j} + \text{rand}(\,)\left(X_{i,b} - X_{i,a}\right) \\ \downarrow \\ X'_{i,\text{new}} = X_{i,j} + \text{rand}(\,)\left(X_{i,g_{\text{best}}} - \left|X_{i,j}\right|\right) - \text{rand}(\,)\left(X_{i,g_{\text{worst}}} - \left|X_{i,j}\right|\right) \end{cases} \tag{11}$$

The optimization process should be carried out in a certain stage, and these stages should be created as complementary and validating each other. This process commonly consists of four stages.

- Process 1: Variables, constraints and constants are determined. Constraints can be specified from standards, former studies or laboratory results. Constants consist of material features and cost values. After that, an initial matrix of recorded data is created.
- Process 2: The best and worst value in the objective function is selected, and the mean value of the objective function is computed to be used in the equations.
- Moreover, minimum and maximum values are checked whether they provide or not. If they do not provide the limitations, the objective function is penalized with big values. Therefore, the new solution matrix is generated.
- After that, the aforementioned processes are found in phase 2.
- Process 3: The objective function in the new solution matrix and the initial matrix are compared with each other, and whichever has the better value is chosen.
- Process 4: The maximum iteration numbers are checked whether they are totally completed. Therefore, the optimization process is decided whether to be continued or not.

Fig. 4 is created to illustrate how the problem can be solved by using a Hybrid Algorithm which is generated by using metaheuristic algorithms known as TLBO and Jaya Algorithm. Flowchart delineates when problem equations, constants and constraints should be used consecutively. Therefore, it is explicitly seen that this chart enables us to find and recognize easily which sequence it should be done.

Multi-objective functions are employed for multiple conflicting objectives that are required to be optimized simultaneously. Therefore, a multi-objective function endeavours to reach a set of solutions that are optimal concerning multiple objectives. These objective functions can be varied in terms of fields that are engineering design, portfolio optimization as well as environmental planning. They are used for minimizing production costs, minimizing environmental impact, minimizing product weight and maximizing production speed. More important properties are chosen to reach optimum results so that appropriate design is obtained easily and effectively.

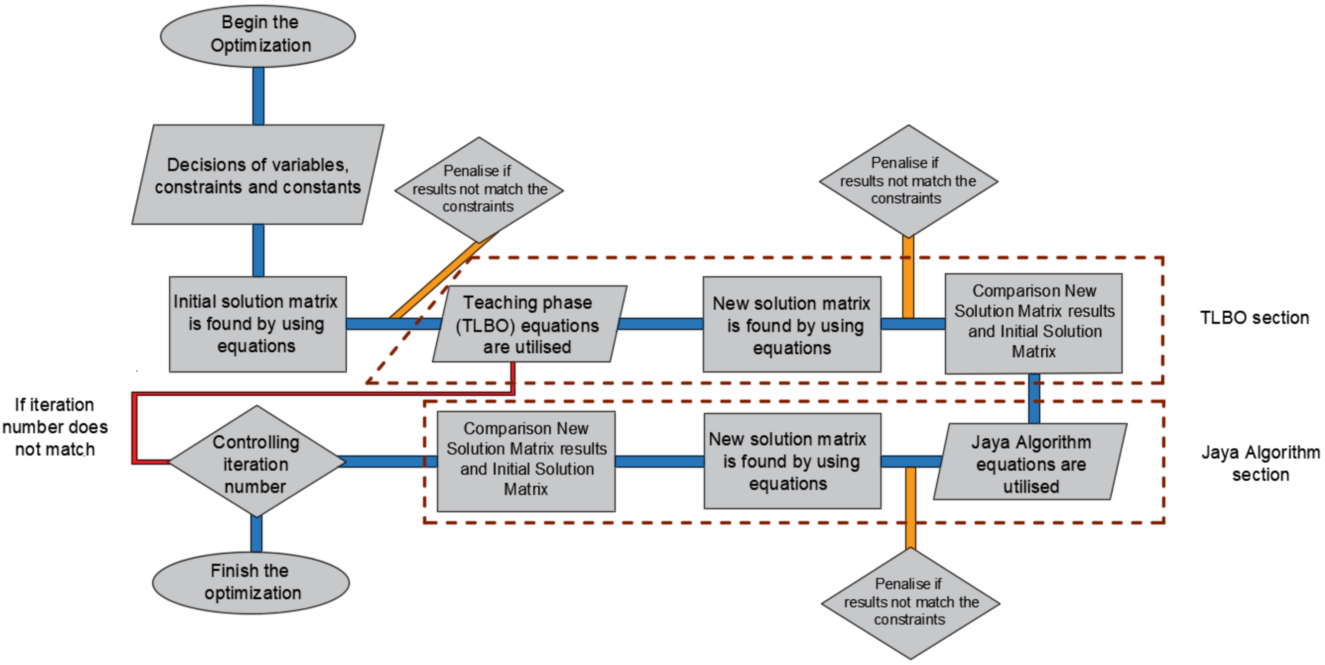

Fig. 4. Flowchart for hybrid algorithm.

Multi-objective optimization has not only a single optimal solution but also a set of optimal solutions which is known as the Pareto-optimal set, and it consists of every potential solution to the problem (Ngatchou et al. 2015). The optimal set of Pareto is an important concept in multi-objective optimization because it enables decision-makers to identify the best compromise between the different objectives (Martinez-Iranzo et al. 2009).

The cost equations are demonstrated in Eqs. (12) and (13). Cost hinges on some factors which are concrete and steel cost (C_c and C_s respectively), beam length (L), cross-section of the beam (b and h) as well as reinforcement area (A_s).

$$\text{Cost}_{\text{concrete}} = C_c \times L \times \left(b \times h - \left(\frac{A_{s,\text{Total}}}{10^6}\right)\right) \tag{12}$$

L_s is recorded as the rebar length, γ_s is the specific density of steel.

$$\textstyle\sum_{i=1} \text{Cost}_{\text{steel}} = C_{s,i} \times L_{s,i} \times \gamma_s \times \frac{A_{s,i}}{10^6} \tag{13}$$

The CO_2 emission equations are delineated in Eq. (14). E_{CO_2} is the CO_2 emission value for materials, V_c is the volume of concrete.

$$\sum CO_2 = C_c \times V_c \times E_{CO_2(c)} + \gamma_s \times \frac{A_s}{10^6} \times E_{CO_2(s)} \tag{14}$$

CO_2 emission and cost are the main goals to generate this problem. Thus, Eq. (15) shows the total values of CO_2 and cost with coefficients. These coefficients can arrange the rate of objective function elements, so they enable us to compare differences between values by changing coefficient values. α and β are not chosen as minus values.

$$f_{\text{total}} = \alpha \times (\text{Cost}_{\text{Total}}) + \beta \times (CO_{2,\ \text{Total}}) \tag{15}$$

Fig. 5 describes multi-objective function processes which are related to CO_2 and cost, and they are calculated as various rates to reach the best solution for desired situations.

4. Example and Discussion

4.1. Numerical example

In order to apply a sustainable and environmentally friendly design, the objective function is specified not only as a cost but also CO_2 emission. These designs are indispensable and crucial for nature. Therefore, the optimization process is done by using metaheuristic algorithms which are generally used for various problems to achieve desired design values. The design was done as pertinent not only to standards but also necessary shear load.

Fig. 6 shows the beam which is used in the numerical example to reach the objective function. The beam design variables are found depending on distributed load, length of the beam, concrete class, cost of materials and amount of materials' CO_2.

Table 1 illustrates the values which are the variables, constraints along with constants. Furthermore, cost values are current values.

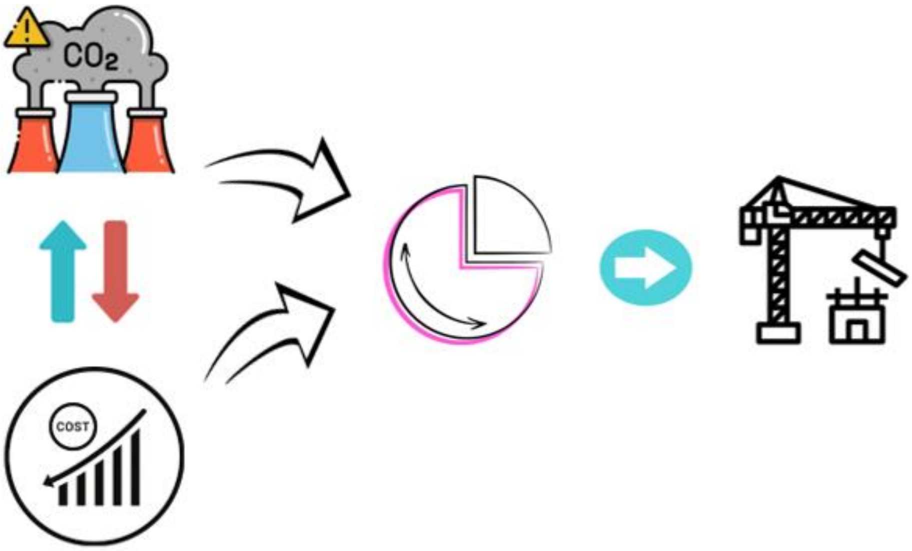

Fig. 5. Multi-objective function example.

Table 1. Numerical example values.

Explanation	Symbol	Unite	Values
Minimum height	$h_{\min}$	mm	400
Maximum height	$h_{\max}$	mm	600
Minimum width	$b_{\min}$	mm	250
Maximum width	$b_{\max}$	mm	400
Compressive strength of concrete	f_{ck}	MPa	30, 40
Length of Beam	L	m	6
Yield strength of concrete	f_{yk}	MPa	420
Specific density of steel	γ_s	t/m^3	7.86
Clear cover	P_c	mm	30
Concrete cost per unit volume	C_c	TL/m^3	30 MPa →2065 40 MPa →2301
CO_2 emission of concrete values	C_{CO_2}	kg/m^3	30 MPa →376 40 MPa →452
Steel cost per unit weight	C_s	TL/ton	Ø>Ø12→16300 Ø10→16600 Ø8→16750

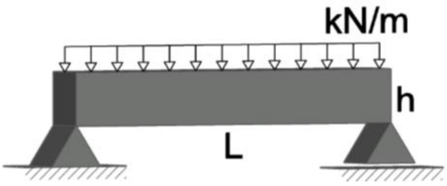

Fig. 6. Illustration of the beam.

Fig. 7 demonstrates the cost of the materials which are the concrete classes and different types of steel. Ø8 and Ø10 are used for stirrups which are necessary for shear force, building standards have some studies about the placement of the clear distance between stirrups. Also, Ø12 and bigger than this rebar is used for longitudinal reinforcement.

Fig. 8 provides information about the CO_2 emission of materials. There are two types of steel which are recycled and not-recycled. These materials impact CO_2 emission, and it is calculated that not-recycled steel is approximately 5 times higher than recycled ones. Some studies give information that not-recycled steel's CO_2 emission changes between 1,800 and 2,000 kg/ton.

4.2. Discussion

According to the numerical example, variables, constraints and constants with equations, an appropriate design is generated in terms of rebar diameters and impact rates of CO_2 and cost in the objective function value. Impact rates were varied in the cases and these are named as Case 1, Case 2 and Case 3. Tables 2 to 6 delineate the results which change according to the diameter of the rebar. Moreover, three cases are generated to compare the rate results between CO_2 emission and cost.

- Case 1 is a 0.5 rate for cost and 0.5 rate for CO2 emission
- Case 2 is a 0.3 rate for cost and 0.7 rate for CO2 emission
- Case 3 is a 0.1 rate for cost and 0.9 rate for CO2 emission

For Table 2, Case 1 and Case 2 have the same results except for objective functions which are different because of rate values, whereas Case 3 variables are different compared to other cases. Fig. 9 shows the results of Table 2.

All cases have the same values in Table 3 except for objective functions. Fig. 10 shows the Table 3 results.

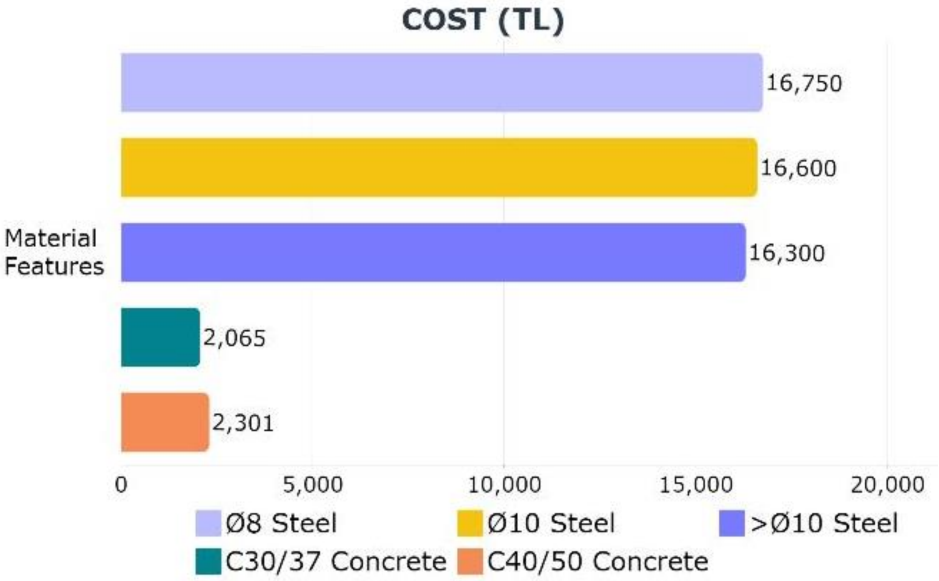

Fig. 7. Cost values.

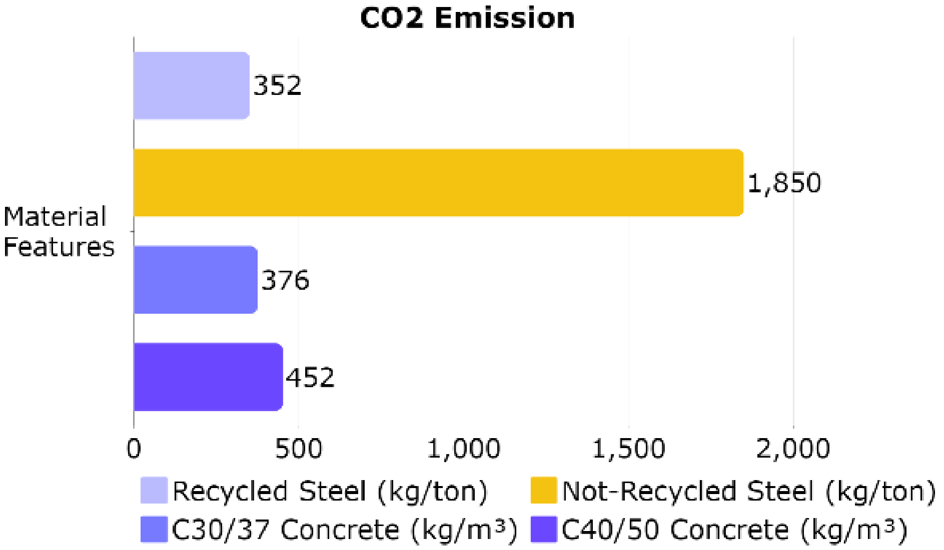

Fig. 8. CO_2 emission values.

Table 2. Ø12 rebar results.

	b	*h*	Reinforcement Area	Concrete Cost	Steel Cost	CO_2 Emission	Objective Function
Case 1	298.67	599.13	678.58	2166.83	1312.85	431.73	1955.71
Case 2	298.67	599.13	678.58	2166.83	1312.85	431.73	1346.12
Case 3	340	521.92	791.68	2146.99	1368.17	429.58	738.14

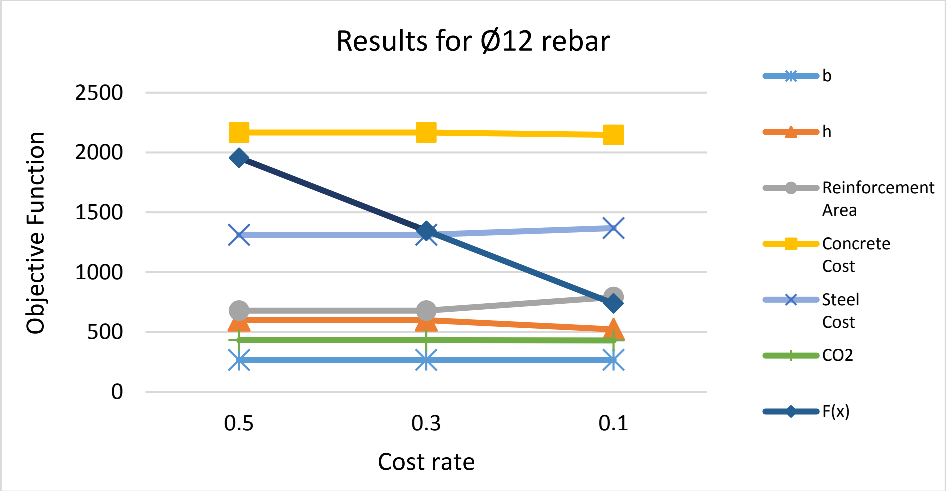

Fig. 9. Results for Ø12 rebar.

Table 3. Ø14 rebar results.

	b	*h*	Reinforcement Area	Concrete Cost	Steel Cost	CO_2 Emission	Objective Function
Case 1	267.33	541.30	769,69	1741.56	1304.31	354.35	1700.11
Case 2	267.33	541.30	769.69	1741.56	1304.31	354.35	1161.81
Case 3	267.33	541.30	769.69	1741.56	1304.31	354.35	623.50

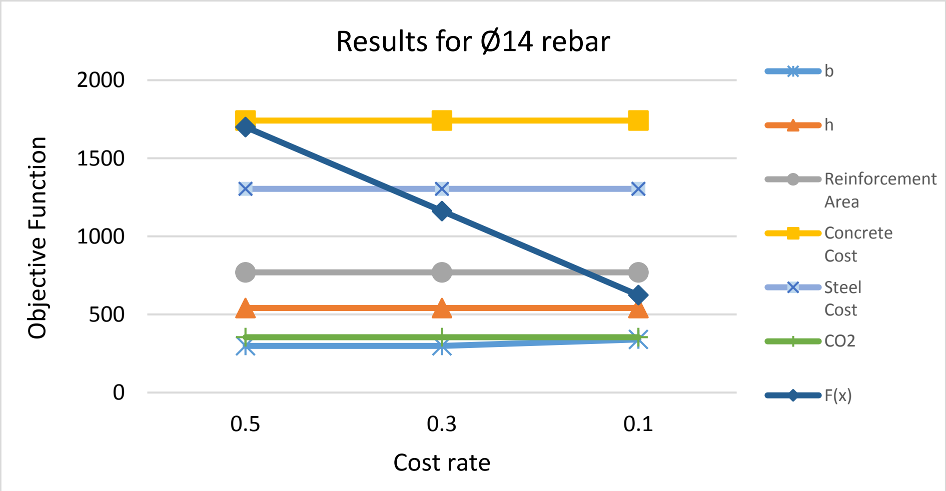

Fig. 10. Results for Ø14 rebar.

It can obviously be seen that Case 2 and Case 3 have the same results, but Case 1 has different results in Table 4. Furthermore, all cases and diameters of rebar have different objective functions which hinge on cost, CO_2 emission as well as the rate between cost and CO_2 emission (Fig. 11). That is why they are generally found different values.

Table 4. Ø16 rebar results.

	b	*h*	Reinforcement Area	Concrete Cost	Steel Cost	CO_2 Emission	Objective Function
Case 1	250.00	524.17	804.25	1571.81	1300.50	323.45	1597.88
Case 2	277.36	436.63	1005.31	1446.03	1402	303.21	1066.66
Case 3	277.36	436.63	1005.31	1446.03	1402	303.21	557.69

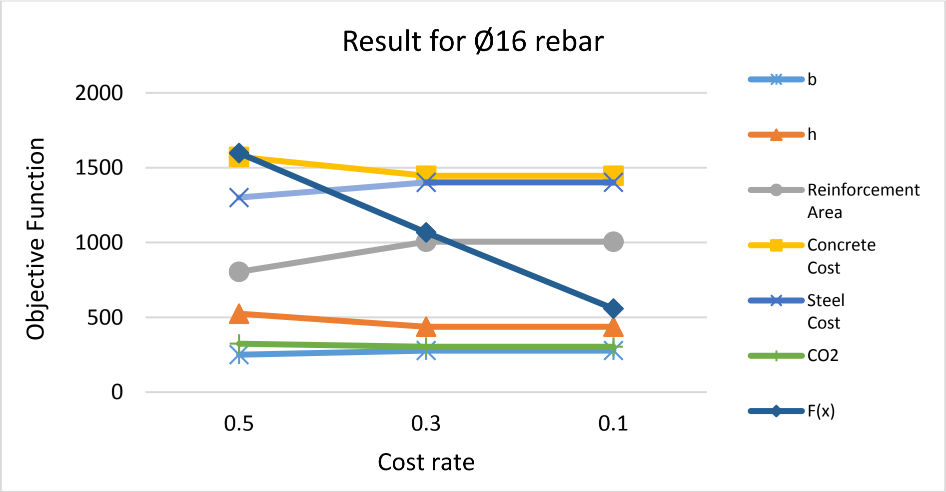

Fig. 11. Results for Ø16 rebar.

Table 5 shows the results of Ø18 rebar and all cases have the same values, it is just objective functions are different. This circumstance is the same as in Table 6. Figs. 12 and 13 display the Table 5 and Table 6 results, respectively.

Table 5. Ø18 rebar results.

	b	*h*	Reinforcement Area	Concrete Cost	Steel Cost	CO_2 Emission	Objective Function
Case 1	250.00	436.89	1017.88	1298.80	1387.80	276.14	1481.37
Case 2	250.00	436.89	1005.31	1298.80	1387.80	276.14	999.27
Case 3	250.00	436.89	1005.31	1298.80	1387.80	276.14	517.18

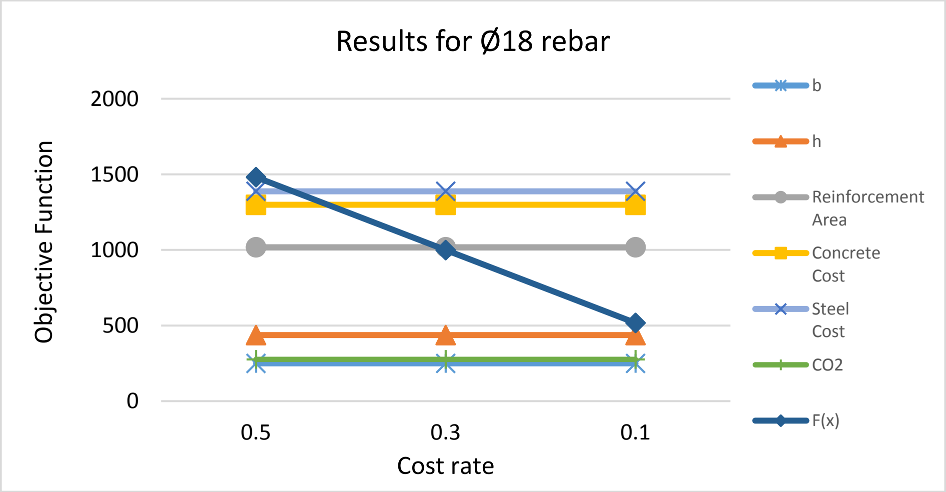

Fig. 12. Results for Ø18 rebar.

Table 6. Ø20 rebar results.

	b	*h*	Reinforcement Area	Concrete Cost	Steel Cost	CO_2 Emission	Objective Function
Case 1	250.00	400.00	1256.64	1180.61	1552.15	258.89	1495.83
Case 2	250.00	400.00	1256.64	1180.61	1552.15	258.89	1001.05
Case 3	250.00	400.00	1256.64	1180.61	1552.15	258.89	506.28

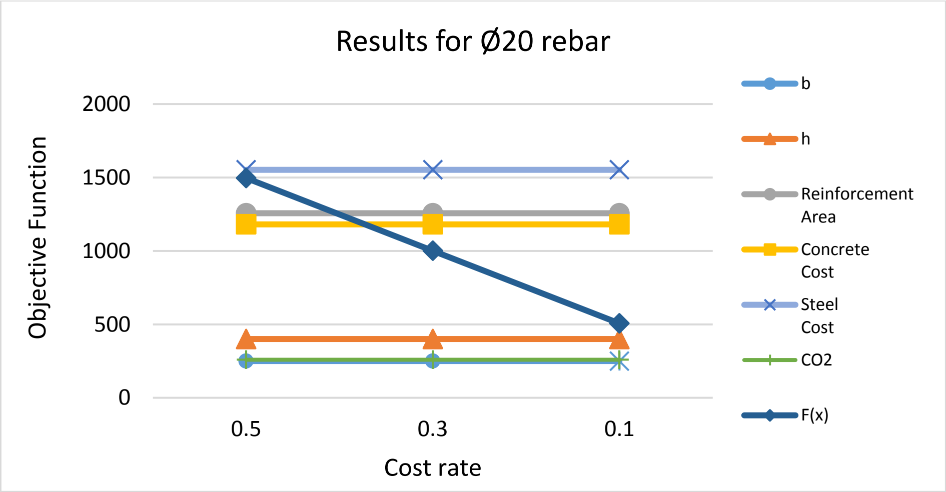

Fig. 13. Results for Ø20 rebar.

The objective function results that are regarding with diameter of steel and steel types that are recycled and not-recycled are demonstrated in Fig. 14. It observed that the differences between recycled and not recycled steel results can be various compared to cases which are “0.5 × cost + 0.5 x CO_2 ; 0.3 × cost + 0.7 × CO_2 ; and 0.1 × cost + 0.9 × CO_2”.

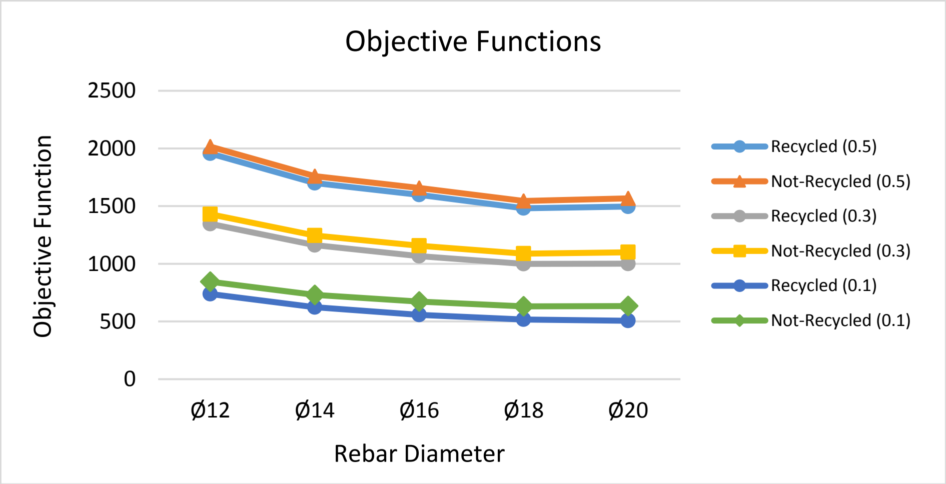

Fig. 14. Comparing objective functions.

That the rate of the cost is chosen as 0.5 for recycled and not-recycled steel has the lowest gap compared to other cases. When the rate s are compared within themselves, different values will be between 3% and 14.4%.

5. Conclusions

Sustainable and environmentally friendly designs are becoming more and more important day by day. One of the biggest reasons for this is that the destruction of nature has increased dramatically in the last few years. Civil engineering, which is one of the fields with a very high CO_2 emission, is at the forefront of the studies carried out and developed. In this context, there are different studies such as materials, optimization and recycling of used materials. In this study, the cost and CO_2 emission optimization for the beam, which is used extensively as a structural element, is carried out with a hybrid algorithm. Such studies are needed in order to use both environmentally friendly and balanced raw materials used in the world. According to certain material, cost and emission values, analyses were made by placing the stirrup and longitudinal reinforcements for the beam both in accordance with the standards and for the shear force. In addition to these analyses, a correlation was established between CO_2 emissions and cost by importance coefficients. With these coefficients, it was ensured that the CO_2 emission value was added to the calculations and used at a higher impact rate than the cost, and comparisons were made. In this way, the reduction of CO_2 emission in the design was provided extra.

Two types of steel were used in the design, one is recycled steel and the other is non-recyclable steel. When these steels are used, analyses were made according to the CO_2 values they emit to nature and the values were recorded. While no difference was observed in the design variables in general, it was observed that there was an increase in the CO_2 emission value. When cases and steel types were compared among themselves, values between objective functions were found between 3% and 14.4%.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

Abubakar J, Benedict ANUM, Iaren C (2021). Design optimization of rectangular RC beams using genetic algorithm. *Usak University Journal of Engineering Sciences*, 4(2), 66-78.

Afshari A, Hare W, Tesfamariam S (2019). Constrained multi-objective optimization algorithms: Review and comparison with application in reinforced concrete structures. *Applied Soft Computing*, 83, 105631.

Aydın Y, Bekdaş G, Nigdeli SM, Işıkdağ Ü, Geem ZW (2023). Comparison of Multilayer Perceptron and Other Methods for Prediction of Sustainable Optimum Design of Reinforced Concrete Columns. In: *Hybrid Metaheuristics in Structural Engineering: Including Machine Learning Applications* (pp. 235-263). Cham: Springer Nature Switzerland.

Aydoğdu İ (2017). Comparison of metaheuristics on multi-objective (cost&C0$_2$) optimization of RC cantilever retaining walls. *Pamukkale University Journal of Engineering Sciences*, 23(3), 221-231.

Bekdaş G, Niğdeli SM, Yücel M, Kayabekir AE (2021). Yapay Zeka Optimizasyon Algoritmaları ve Mühendislik Uygulamaları. 1st ed., Seçkin Yayıncılık, Ankara, Türkiye.

Cakiroglu C, Bekdaş G (2022). Optimization of axial load carrying capacity of CFST stub columns. *Challenge Journal of Concrete Research Letters*, 13(1), 1-4.

Cakiroglu C, Islam K, Bekdaş G, Billah M (2021a). CO$_2$ emission and cost optimization of concrete-filled steel tubular (CFST) columns using metaheuristic algorithms. *Sustainability*, 13, 8092.

Cakiroglu C, Islam K, Bekdaş G, Kim S, Geem ZW (2021b). CO$_2$ emission optimization of concrete-filled steel tubular rectangular stub columns using metaheuristic algorithms. *Sustainability*, 13, 10981.

Cakiroglu C, Islam K, Bekdaş G (2023a). Manta Ray Foraging and Jaya Hybrid Optimization of Concrete Filled Steel Tubular Stub Columns Based on CO$_2$ Emission. In: *Hybrid Metaheuristics in Structural Engineering: Including Machine Learning Applications* (pp. 111-125). Cham: Springer Nature Switzerland.

Cakiroglu C, Islam K, Bekdaş G, Nehdi ML (2023b). Data-driven ensemble learning approach for the optimal design of cantilever soldier pile retaining walls. *Structures*, 51, 1268-1280.

Camp CV, Assadollahi A (2015). CO$_2$ and cost optimization of reinforced concrete footings subjected to uniaxial uplift. *Journal of Building Engineering*, 1(3), 171-83.

Çoşut M, Bekdaş G, Niğdeli SM (2023). Comparison of different regulations and metaheuristic algorithms in beam design. *International Journal of Engineering and Applied Sciences*, 15(1), 1-18.

Csébfalvi A (2009). A hybrid meta-heuristic method for continuous engineering optimization. *Periodica Polytechnica*, 53(2), 93-100.

Doğangün A (2019). Betonarme Yapıların Hesap ve Tasarımı. 16th ed., Birsen Yayınevi, İstanbul, Türkiye.

Habert G, Roussel N (2009). Study of two concrete mix-design strategies to reach carbon mitigation objectives. *Cement and Concrete Composites,* 31(6), 397-402.

Joyner MD, Gardner C, Puentes B, Sasani M (2021). Resilience-based seismic design of buildings through multi-objective optimization. *Engineering Structures,* 246, 113024.

Kara G, İbiç A, Yağcıoğlu E (2018). Çimento sektöründen kaynaklanan sera gazı emisyonları. *Ulusal Çevre Bilimleri Araştırma Dergisi*. 1(2), 87-90.

Kayabekir AE, Arama ZA, Bekdaş G, Nigdeli SM, Geem ZW (2020.) Eco-friendly design of reinforced concrete retaining walls: Multi-objective optimization with harmony search applications. *Sustainability*, 12(15), 6087.

Khajehzadeh M (2016). A new hybrid algorithm for CO$_2$ emissions optimization of retaining walls. *International Journal of Advances in Mechanical and Civil Engineering,* 3(1), 7-11.

Lepš M, Šejnoha M (2003). New approach to optimization of reinforced concrete beams. *Computers & structures.* 81(18-19), 1957-1966.

Li ZG (2011). Development and application of eco-friendly concrete. *Advanced Materials Research,* 250, 3827-3836. Trans Tech Publications Ltd.

Martínez-Iranzo M, Herrero JM, Sanchis J, Blasco X, García-Nieto S (2009). Applied pareto multi-objective optimization by stochastic solvers. *Engineering Applications of Artificial Intelligence*, 22(3), 455-465.

Medeiros GF, Kripka M (2012). Harmony search algorithm applied to the optimization of reinforced concrete columns. *Proceedings of the International Conference on Engineering Optimization,* Rio de Janeiro, Brazil.

Ngatchou P, Zarei A, El-Sharkawi A (2005). Pareto multi-objective optimization. *Proceedings of the 13th International Conference on Intelligent Systems Application to Power Systems,* 84-91.

Ocak A, Nigdeli SM, Bekdaş G, Işıkdağ Ü (2023). Machine learning application of structural engineering problems. In: *Hybrid Metaheuristics in Structural Engineering: Including Machine Learning Applications* (pp. 179-198). Cham: Springer Nature Switzerland.

Paya-Zaforteza I, Yepes V, Hospitaler A, Gonzalez-Vidosa F (2009). CO$_2$-optimization of reinforced concrete frames by simulated annealing. *Engineering Structures,* 31(7), 1501-1508.

Rao RV (2011). Teaching-learning based optimization: A novel method for constrained mechanical design optimization problems. *Computer-Aided Design*, 43, 303-315.

Rao RV (2016). Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems. *International Journal of Industrial Engineering Computations,* 7, 19-34.

TBDY (2018). Türkiye Bina Deprem Yönetmeliği. Afet ve Acil Durum Yönetimi Başkanlığı, Ankara, Türkiye.

Temur R (2021). Optimum design of cantilever retaining walls under seismic loads using a hybrid TLBO algorithm. *Geomechanics and Engineering*, 24, 237-251.

TS 500 (2000). Betonarme Yapıların Tasarım ve Yapım Kuralları (Requirements for Design and Construction of Reinforced Concrete Structures). Turkish Standards Institute, Ankara, Türkiye.

URL-1 (2023). https://ourworldindata.org/co2-emissions, last accessed 2023/05/01.

Yang XS (2012). Flower pollination Algorithm for Global Optimization. *UCNC*, 240-249.

Yang XS, Gandomi AH (2014). Bat Algorithm: A novel approach for global engineering optimization. *Engineering Computations,* 29(5), 464-483.

Yeo D, Potra F, A (2015). Sustainable design of reinforced concrete structures through CO$_2$ emission optimization. *Journal of Structural Engineering,* 141(3), B4014002.

Yucel M, Bekdas G, Isikdag U, Apak S (2021). Optimum modelling for rectangular shape reinforced concrete (RC) beam with the aim of minimum CO$_2$ emission. *Journal of Environmental Protection and Ecology,* 22(5), 1992-2002.

CHALLENGE JOURNAL OF CONCRETE RESEARCH LETTERS 14 (4) (2023) 107–117

Challenge Journal of Concrete Research Letters

Research Article

Effect of hemp and basalt fiber on fracture energy of cement-based composites: a comparative study

Adil Gultekin [a]

[a] *Department of Civil Engineering, Düzce University, 81620 Düzce, Türkiye*

ABSTRACT

Fiber-reinforced composites are one of the most used construction materials. Nowadays, some types of fibers like steel, carbon, glass and basalt are commonly used in these composites. However, the production of these fibers consumes natural resources and a high amount of energy. Researchers have started working on natural fibers to reduce commonly used fibers productions' drawbacks for more sustainable composites. However, the effect of natural fibers on the properties of cement-based composites -especially fracture energy- still needs further research and comparing with the behavior of commonly used fibers. In this study the effect of hemp fiber on the mechanical properties and fracture energy of cement-based fiber-reinforced mortar mixtures was investigated. The results were compared with those of the basalt fiber-reinforced mixtures. The results showed that the flexural strength and fracture energy improved with the use of hemp and basalt fiber compared to the fiber-free mixture. The flexural strength increased up to 10.7% and 19.6% with the inclusion of hemp and basalt fibers, respectively. The mean peak load and fracture energy of hemp fiber-reinforced mortar was higher than those of the fiber-free mixture by 32.2% and 17.9%, respectively. The corresponding values for basalt fiber addition 60.8% and 146.4%.

ARTICLE INFO

Article history:
Received 26 July 2023
Revised 14 August 2023
Accepted 24 August 2023

Keywords:
Hemp fiber
Basalt fiber
Fracture energy
CMOD
Cement mortar

1. Introduction

Concrete is the most commonly used construction material in the world (Jianbing et al. 2022). Despite providing much superiority, concrete has several disadvantages, such as low tensile strength and brittleness (El-Abbasy 2022). Fibers can be used to overcome these issues and improve properties such as ductility, toughness, and durability in cement-based building materials (Vairagade and Dhale 2023). To enhance properties of concrete, it is possible to use various types of fibers like steel, glass, polypropylene (Li et al. 2022), PVA, basalt, etc. (Zhao et al. 2016). However, it is known that the production of these types of fibers results in various drawbacks, like carbon emission, and the consumption of different types of resources (Chen et al. 2023).

Nowadays, various types of natural fibers are being used to enhance some properties of concrete due to their characteristics such as low cost, sustainability, renewability (Abdalla et al. 2022), unlimited availability, biodegradability, recyclability (Suardana et al. 2011) as well as low density, high acoustic damping and reduced industrial fuel expense (Ahmad and Zhou 2022). Interest in natural fibers is expected to increase in the coming years (Sullins et al. 2017).

Hemp is a well-known plant species and industrial hemp is used in different sectors like textile, food, automobile, biofuel and construction (Grubesa et al. 2018). The main components of hemp fiber are cellulose, hemicellulose and lignin (Stevulova et al. 2022). Studies are carried out on the use of fibers obtained from the hemp plant in the production of fiber concrete. Although there are limited studies in the literature, the findings revealed that using hemp fiber in fiber-reinforced concrete is possible. Li et al. (2006) investigated the effect of aggregate size, mixing method, length and amount of hemp fiber on

---

* *Corresponding author.* Tel.: +90-850-800-8181 ; Fax: +90-380-542-1103 ; E-mail address: adilgultekin@duzce.edu.tr (A. Gultekin)

ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2023.04.002

some physical and mechanical properties of hemp fiber-reinforced concrete. For this purpose, 10, 20 and 30 mm long fibers were used in different dosages and a total of 30 concrete mixtures were produced. Researchers reported that it is possible to increase the flexural toughness up to 143.6%, 30.3% and 57.4%, respectively, by using hemp fiber in concretes with 20, 14 and 7 mm maximum size aggregates.

Çomak et al. (2018) examined the effect of hemp fiber dosage and length on the mechanical properties of cement mortar mixtures. 6, 12, 18 mm long fibers were utilized at three dosages of 1, 2, and 3% by volume. It was determined that the flexural strength increased in the range of 1.2-16.9% with fiber inclusion. Another finding of the study was that, in mortars containing 6 mm and 12 mm long fibers, the flexural strength improved as the fiber content increased, while the opposite situation was observed when 18 mm long fibers were used. In a similar research Ruano et al. (2020) conducted a study on the flexural behavior of sugarcane bagasse and hemp fiber-reinforced mortars. The load-CMOD relationship of the mixtures was determined and the researchers stated that the flexural toughness increased with the hemp fiber addition. Zhou et al. (2017) explored the effect of the treatment of hemp fiber on some properties of concrete and stated that with the treatment, the 28-day compressive and tensile strength, as well as the critical stress intensity factor, critical strain energy release rate and fracture toughness were affected positively. Kaplan and Bayraktar (2021) reported that the flexural strength of cement mortar increased with the inclusion of hemp fiber of 5, 10 and 20 mm length and 1, 2, 3% by the weight of cement.

Basalt fibers are produced with lower energy consumption than commonly used fiber types such as steel, glass, and carbon. They also have advantages such as high tensile strength, good durability, and corrosion resistance (Al-Rousan et al. 2013). The basalt fibers are widely utilized at different civil engineering applications, and it is known that these fibers improved mechanical properties of concrete (Zhou et al. 2023). Kabay (2014) investigated the effects of 12 and 24 mm long basalt fibers inclusion with 0.07% and 0.14% dosages by volume on the properties of concrete mixtures produced with two different water/cement ratios (0.45 and 0.60). The researcher stated that with the addition of basalt fibers, the fracture energies of concretes prepared with 0.45 and 0.60 water/cement ratios increased up to 112.6% and 140.2%, respectively. In addition, the flexural strengths of concrete were improved up to 10.4% and 15.9% with fiber usage. Arslan (2016) investigated the effect of basalt fiber dosage on fracture energy of notched beam concrete specimens having a water/cement ratio of 0.5. The fibers were used at 0.5, 1, 2, and 3 kg/m^3 dosages, and fracture energies were calculated with crack mouth opening displacements (CMOD). The researcher reported that with basalt fiber addition, flexural strength and fracture energy increased up to 25.4% and 28.6%, respectively, and the optimum fiber dosage for fracture energy was 2 kg/m^3. In a similar study, Kizilkanat et al. (2015) investigated the effects of basalt fiber dosage on the properties of concrete. The fibers were used at 0.25%, 0.50%, 0.75%, and 1% by volume, and the strength and fracture properties were determined. The researchers stated that basalt fiber increased the splitting tensile strength, flexural strength, peak load, and fracture energy. With the increase in fiber dosage, the fracture energies continuously improved and became 51% higher than the fiber-free mixture at 1% dosage.

In spite of several studies, the effect of natural fibers on the fresh properties, sorptivity, strength and fracture energy of cement-based composite still needs to be compared with those of the commonly used fibers like glass, steel, basalt, carbon, etc. This study determined the effect of hemp fiber on flow diameter, unit weight, water absorption, coefficient of sorptivity, compressive and flexural strength as well as fracture energy of the cement mortar mixtures. The experimental work was divided into two different phases. Firstly, the effect of the fiber type (basalt or hemp), fiber dosage (0.125, 0.25, 0.5, or 1% by volume), and fiber length (6 or 18 mm) on fresh properties and mechanical strength were investigated. After that, the selected hemp-fiber and basalt-fiber reinforced mixtures were subjected to 3-point bending test, and the fracture energies of samples were determined using the force-crack mount opening displacement relationship. The results showed that the mechanical properties and fracture energies improved with the use of hemp fiber compared to those of the plain (fiber-free) mixture. However, basalt fibers were much more effective on these properties.

2. Materials and Method

2.1. Materials

CEM I 42.5 R type Portland cement, tap water and CEN standard sand conformed to TS EN 196-1 standard were used in the production of mixtures. Besides, to achieve acceptable workability, a commercial polycarboxylate-based plasticizer was utilized. The chemical composition and some properties of cement are given in Table 1. In the preparation of fiber-reinforced mortar mixtures, commercial basalt fiber 13-20 µm in diameter, 4000-4500 MPa in tensile strength, 88 GPa in modulus of elasticity, and natural hemp fiber was used. The specific gravities of basalt and hemp fiber were 2.80 and 0.85, respectively.

The preparation process of the hemp fibers and the image of the fibers are shown in Figs. 1 and 2, respectively. The dried hemp bundles were provided (Fig. 1a and 1b), the hurds were manually separated from the bulk (Fig. 1c), and bundle of fiber were obtained (Fig. 1-d). Then hemp fibers were cut to 6 and 18 mm by hand (Fig. 2).

SEM micrographs of fibers with different magnifications are given in Fig. 3. The diameter of basalt fibers was around 20 µm. On the contrary, the geometry of hemp fiber was irregular and generally extended in two directions. The widths of hemp fibers were more than their thicknesses, and the width of fibers varied from fiber to fiber from 10 µm up to 1000-1500 µm. Moreover, the surface of hemp fiber was significantly rougher than that of the basalt fiber.

Table 1. Chemical composition and some properties of cement.

Compound	% (by weight)	Mechanical properties	
CaO	63.06	Compressive strength	
SiO_2	18.53	7 days	38.4 MPa
Al_2O_3	5.21	28 days	47.2 MPa
Fe_2O_3	3.65		
MgO	1.01	Physical properties	
Na_2O	0.48	Specific gravity	3.11
K_2O	0.64	Initial setting time	210 mins.
SO_3	3.20	Final setting time	315 mins.
Free CaO	0.91	Blaine specific surface area	3420 cm^2/g
Loss on ignition	2.94		
Insoluble residue	0.10		

Fig. 1. Preparation of hemp fibers:
(a),(b) Hemp fibers with hurds; (c) Cleaning fibers from hurds; (d) Hemp fibers before cutting.

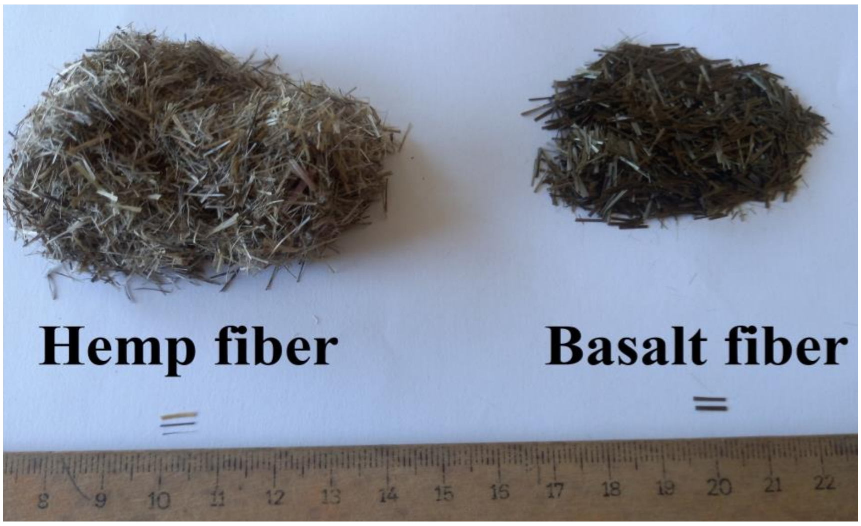

Fig. 2. Photos of fibers.

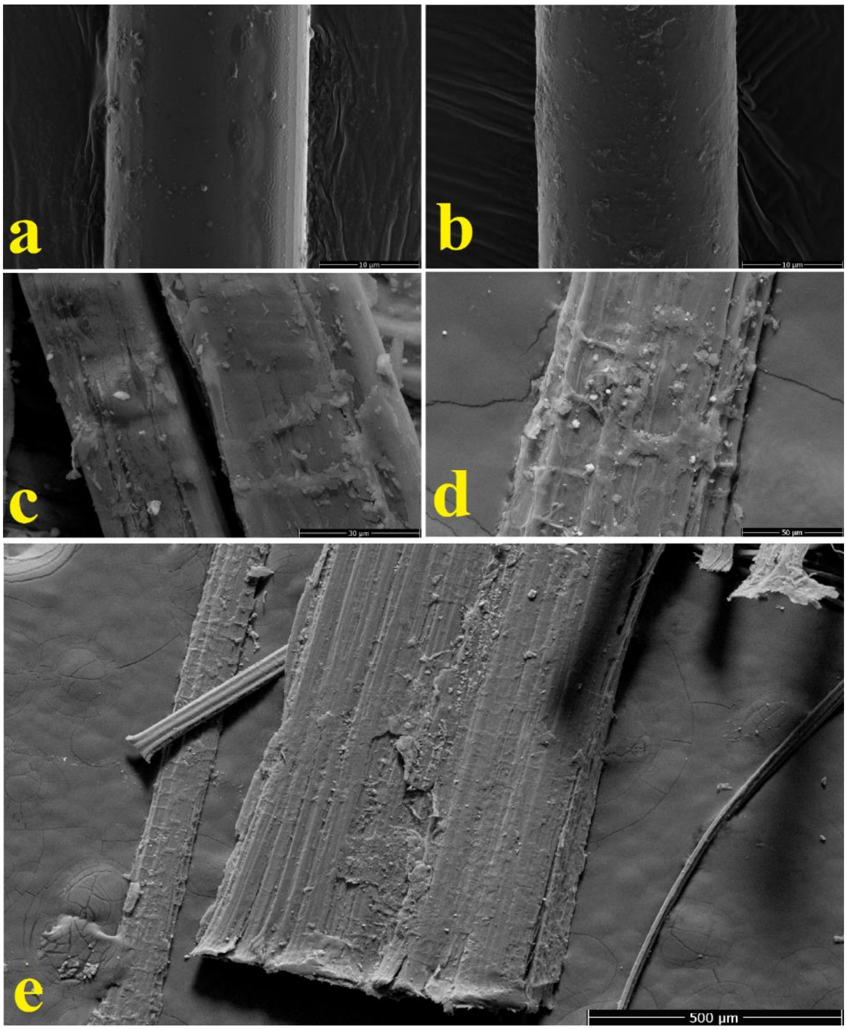

Fig. 3. SEM images of fibers: (a),(b) Basalt fiber; (c),(d),(e) Hemp fiber.

2.2. Method

Mixtures were prepared with an automatic mortar mixer. Firstly, sand, cement and fibers were dry mixed at 62.5 rpm for 60 seconds. Water and plasticizer were combined and added to the bowl. The mixer was operated for 90 seconds at 62.5 rpm. The material adhered to the wall of the bowl was scraped within approximately 15 seconds, then the mixer was run for another 90 seconds at 125 rpm. The fresh mixtures were poured into the molds in two layers, and each layer was compacted by a jolting table with 25 jolts. Samples were stored in laboratory conditions for 24 hours, demolded after this time, and cured for 27 days at the curing pool. All hardened mortar tests were performed at the age of 28 days.

40 mm x 40 mm x 160 mm prismatic specimens were used to determine the coefficient of sorptivity, water absorption and unit weight. Besides, notched specimens (50 mm x 50 mm x 240 mm), with a 10 mm notch height and 3 mm notch width, were prepared for the fracture energy tests. The compressive strength tests were carried out on the broken portions of the specimens after flexural strength tests. Three specimens were used for all tests carried out in the study (except compressive strength which was done on six specimens), and the average values were reported. The flow diameter, coefficient of sorptivity, compressive and flexural strengths were determined in accordance with ASTM C1437, ASTM C1585, ASTM C349 and ASTM C348 standards, respectively. Fracture energy tests were carried out using a 3-point bending test setup with a displacement-controlled device. The rate of loading was 0.01 mm/minute, and the crack mouth opening displacements (CMOD) were measured with a clip-on gage. A strong adhesive was used to connect metal blades to the samples' bottom surfaces, and clip-on gage was attached to the sharp edges of knifes. The experimental setup and sample geometry are shown in Fig. 4. When the peak load dropped by 95%, the test was ended. The graphs of the force-CMOD relationship were drawn, and the fracture energy was calculated using Eq. (1) with the suggestion of Rilem (1985). However, instead of force-deformation curves, force-CMOD curves were used.

$$G_F = \frac{W_0 + mg\delta_0}{A} \tag{1}$$

In this equation, W_0, mg, δ_0 and A represent the area under force-CMOD curve (N·mm), the weight of the specimen between the supports (N), the maximum crack opening (mm) and area of the midspan cross-section of the specimens without notch (mm^2), respectively.

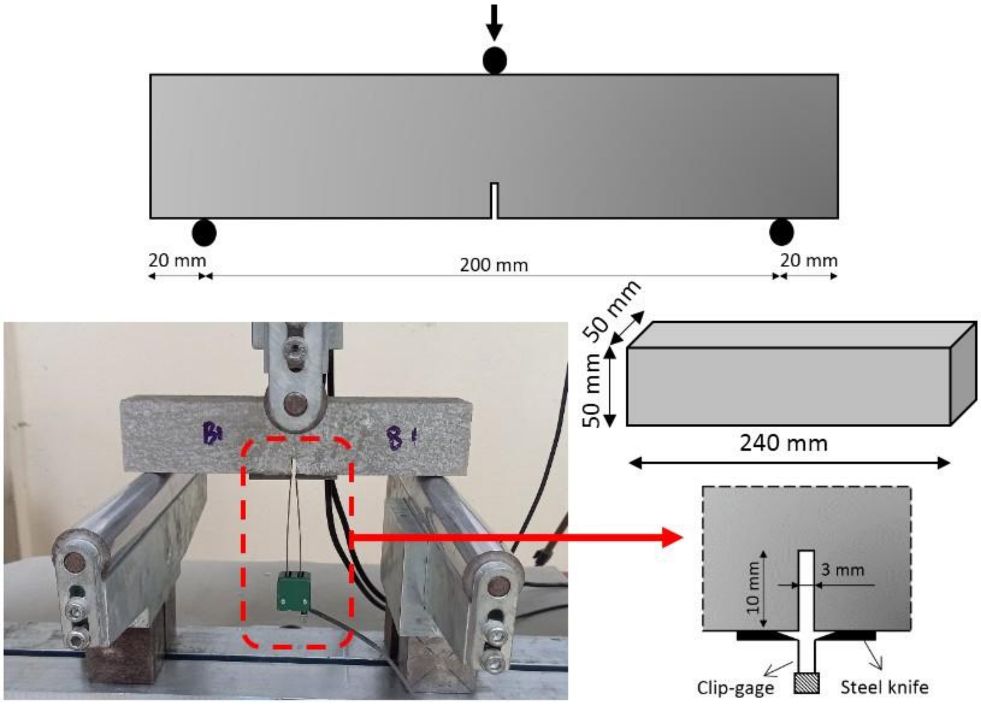

Fig. 4. Fracture energy test setup, geometry of specimen and detail of notch.

2.3. Mixtures

The experimental study is divided into two different phases. The compressive and flexural strengths of the fiber-free mixture and fiber-reinforced mixtures were determined at the first stage. The length and dosage of fibers were the selected variable parameters. In this regard, a total of 16 fiber-reinforced mortar mixtures were prepared with two fiber types (basalt and hemp), two fiber lengths (6 and 18 mm) and four fiber dosages (0.125, 0.25, 0.50 and 1% by volume). In addition to the reference mixture, two mixtures were selected for each fiber type regarding the flexural strength test results for the next phase.

In the second stage, the fracture energy, coefficient of sorptivity and water absorption capacity values of the selected mixtures were determined, and the effect of fiber inclusion on these properties was evaluated comparatively. The proportions and some properties of mixtures are given in Table 2, and the designation of the mixtures is explained in Fig. 5.

Table 2. Ingredients and some properties of mixtures.

Mixture	Ingredients (g)					
	Cement	Sand	Water	Plasticizer	Hemp fiber	Basalt fiber
Control	450	1350.0	225	2	-	-
HS-0.125	450	1348.3	225	2	0.96	-
HS-0.25	450	1346.6	225	2	1.92	-
HS-0.50	450	1343.3	225	2	3.83	-
HS-1.0	450	1336.5	225	2	7.67	-
HL-0.125	450	1348.3	225	2	0.96	-
HL-0.25	450	1346.6	225	2	1.92	-
HL-0.50	450	1343.3	225	2	3.83	-
HL-1.0	450	1336.5	225	2	7.67	-
BS-0.125	450	1348.3	225	2	-	3.12
BS-0.25	450	1346.6	225	2	-	6.24
BS-0.50	450	1343.3	225	2	-	12.48
BS-1.0	450	1336.5	225	2	-	24.96
BL-0.125	450	1348.3	225	2	-	3.12
BL-0.25	450	1346.6	225	2	-	6.24
BL-0.50	450	1343.3	225	2	-	12.48
BL-1.0	450	1336.5	225	2	-	24.96

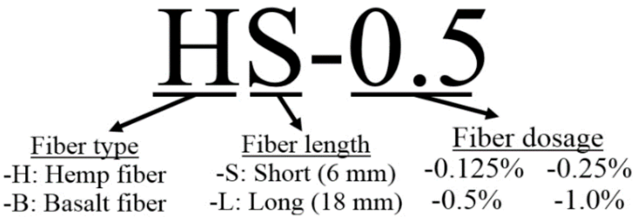

Fig. 5. Designation of mixtures.

3. Results and Discussion

3.1. Flow diameter and unit weight

Figs. 6 and 7 illustrate the flow diameter and unit weight values of mixtures. As seen from the figures, the flow diameter and unit weight of the fiber-free mixture was the highest, as expected. Irrespective of fiber type and length, raising the dosage of fiber from 0.125% to 1% resulted in a gradual decrease in flow diameter. The reductions due to basalt fiber addition were higher than that of hemp fiber addition. This phenomenon is probably due to basalt fiber's high surface area/volume ratio. The mixtures with 1% fiber inclusion had the lowest flow diameter in each series. Increasing the fiber dosage also decreased the fiber-reinforced mixtures' unit volume weight. This situation was more considerable in the mixtures including 1% fiber.

3.2. Compressive and flexural strength

The flexural and compressive strength values of mixtures are given in Figs. 8 and 9, respectively. As seen from the figure, irrespective of the fiber type and length, 0.125% fiber inclusion did not have a meaningful effect on the flexural strength due to insufficient fiber dosage. The results were similar with the addition of 0.25% hemp fiber. 1% fiber-reinforced mixtures in all series had the lowest flexural strength values due to their low workability. Hemp and basalt fiber reinforced mortars containing 0.5% long and 0.5% short fibers have the highest flexural strengths in their series, with 6.2 and 6.7 MPa, respectively. These mixtures were selected for the water absorption, sorptivity and fracture energy tests.

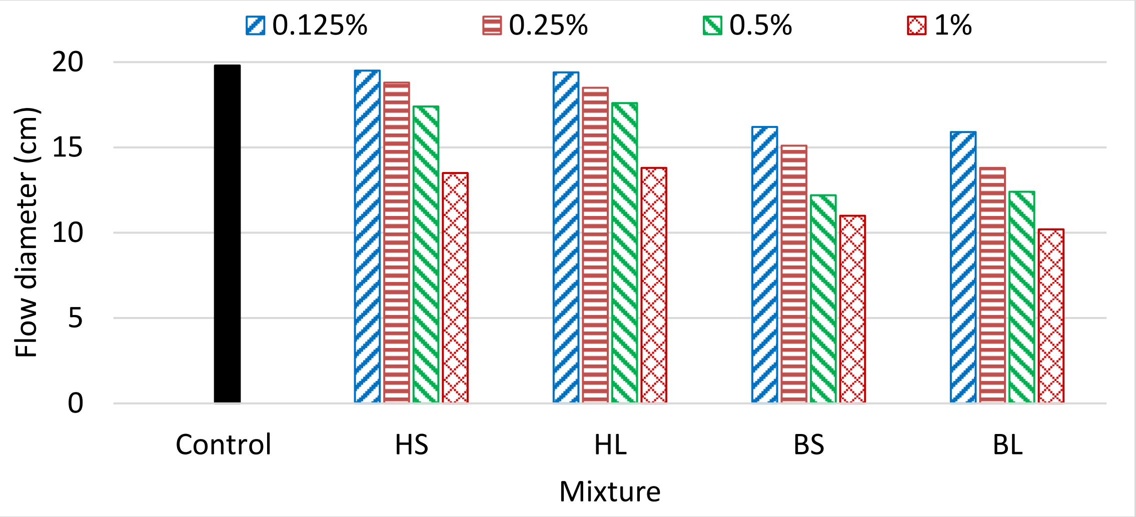

Fig. 6. Flow diameters of the mixtures.

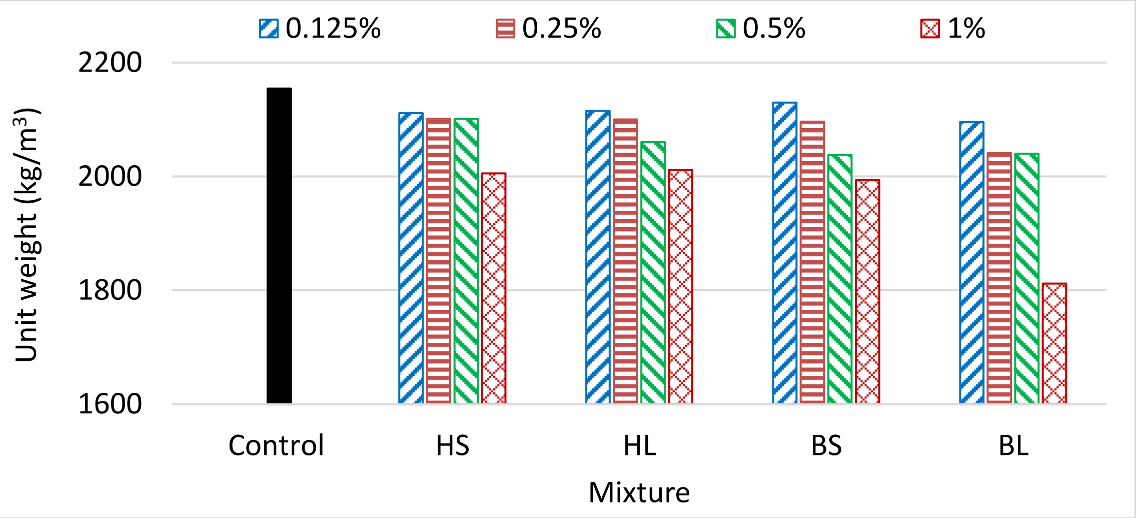

Fig. 7. Unit weights of the mixtures.

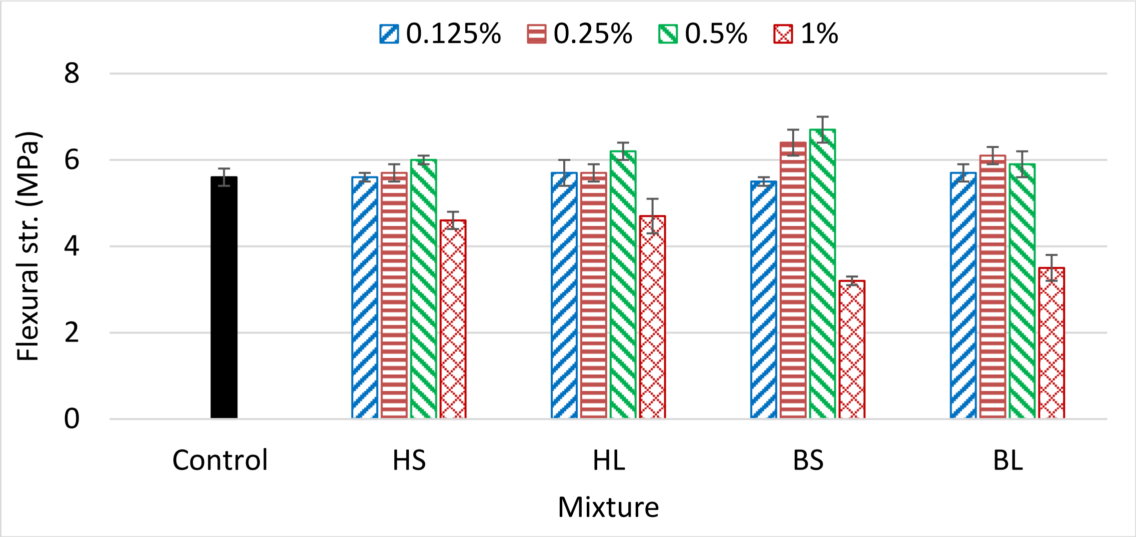

Fig. 8. Flexural strengths of the mortar mixtures.

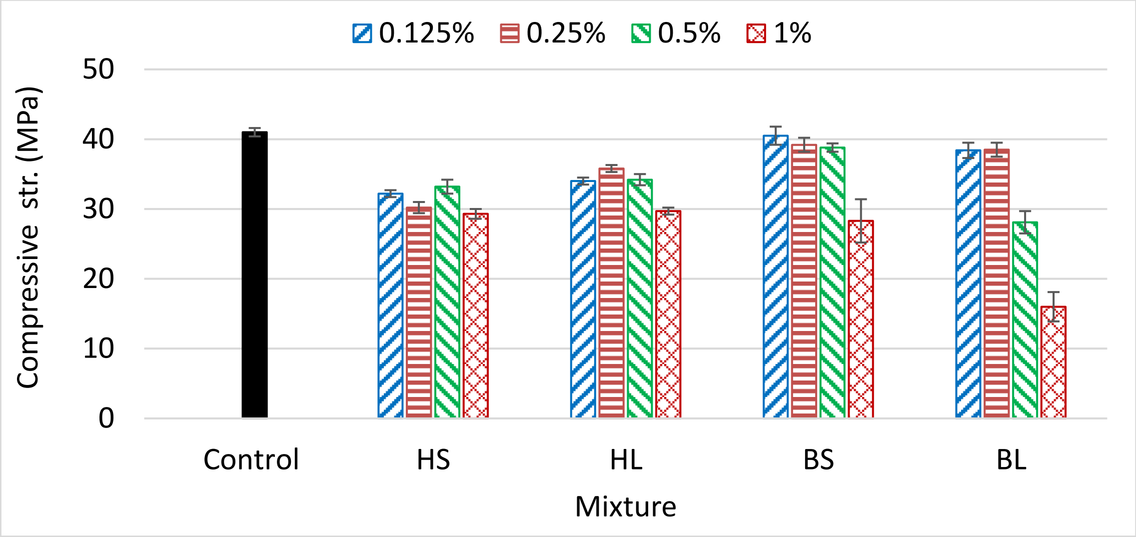

Fig. 9. Compressive strengths of the mortar mixtures.

On the other hand, test results revealed that fiber inclusion had a negative effect on the compressive strength. The compressive strength of hemp fiber-reinforced mortars was 12.7-28.5% lower than that of the reference mortar. Besides, at lower dosages, the basalt fiber inclusion did not significantly affect the compressive strength. However, with the increase in fiber dosage, both flow diameter and strength decreased progressively probably due to the effect of basalt fiber's high surface area/volume on workability and consequently on compactibility of the mixtures. Uygunoğlu et al. (2022) investigated the effect of PVA fiber content on the properties of cement-based mortar. The researchers reported that the compressive and flexural strengths increased with the addition of 2% fiber but at higher dosages it had a negative impact on the mechanical properties. The fact was attributed to the workability and placement issues caused by the increasing fiber dosage. In a similar study, Şahan et al. (2021) examined some properties of polypropylene fiber-reinforced concretes. The researchers reported that the flexural and compressive strengths increased compared to those of the control sample at the optimum fiber dosage of 0.22%; beyond this dosage, the strength decreased.

3.3. Fracture energy

The force-deflection and force-CMOD curves of three specimens of each mixture are given in Figs. 10 and 11, respectively. The peak load, maximum deflection, maximum CMOD values and the area under the curves increased with fiber inclusion. In this respect, the inclusion of basalt fiber had a higher positive effect than that of the hemp fiber.

The peak load, deflection corresponding to the peak load and fracture energy values are given in Fig. 12. With the addition of hemp and basalt fiber, the mean peak load increased by 32.2% and 60.8%, respectively. Although the hemp fibers enhanced the peak load and fracture energy, the amount of increase was considerably lower than that of the basalt fibers.

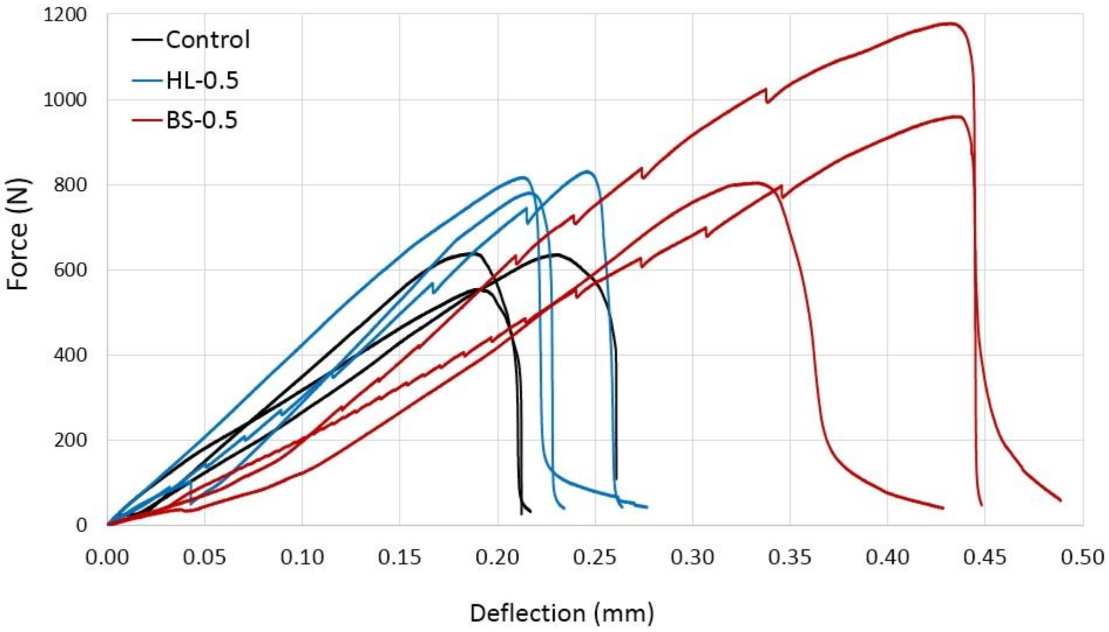

Fig. 10. Force-deflection relationships of the samples.

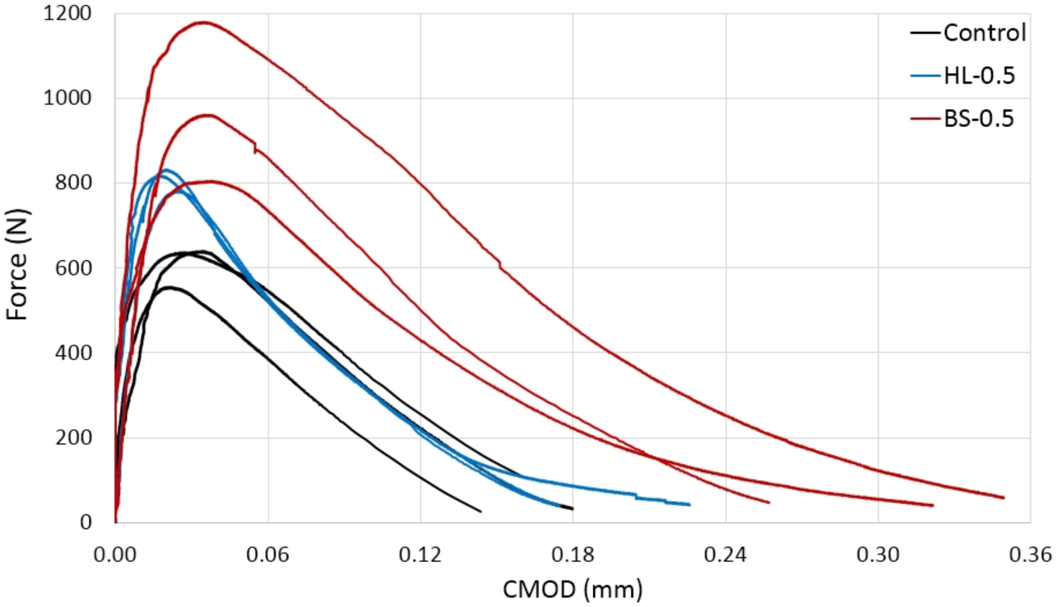

Fig. 11. Force-CMOD relationships of the samples.

Similarly, mean deflection values corresponding to the peak load of hemp and basalt fiber-reinforced mortars were 10.9% and 97.5% higher than that of the control sample, respectively. Compared to that of the reference mixture, the deflection corresponding to the peak load of the fiber-reinforced mixes was greater. The role of fibers in increasing the first cracking point and their bridging effect upon crack propagation is obvious. Fiber inclusion increased the fracture energy too, and the fact was more pronounced with basalt fiber addition. The increment rates were 17.9% and 146.4% for hemp and basalt fiber addition, respectively. Ruano et al. (2020) also reported that the flexural toughness of concrete improves with hemp fiber addition. It is known that fibers transfer the load and show a bridging effect on the fracture surface, resulting in delaying the connection of the cracks (Bencardino et al. 2010) with the mechanisms of debonding, bridging, pull-out and failure (Abbas and Khan 2016). During the fracture energy test, the bridging effect delaying the crack propagation was obvious. At the end of the test, visual observation on the fracture surfaces of specimens revealed the debonding of the fibers and probably fracture of some of them. Arslan (2016) reported that with the use of basalt fiber, the fracture energies of fiber-reinforced concrete increased by 6.8-28.6% depending on the fiber dosage. In a similar study, the increment rate of the fracture energy with basalt fiber inclusion was stated to be in between 3-51% (Kizilkanat et al. 2015). According to a study on fiber-reinforced self-compacting concretes, Gultekin et al. (2022) stated that it is possible to increase the fracture energy with basalt fiber addition up to 30.4%.

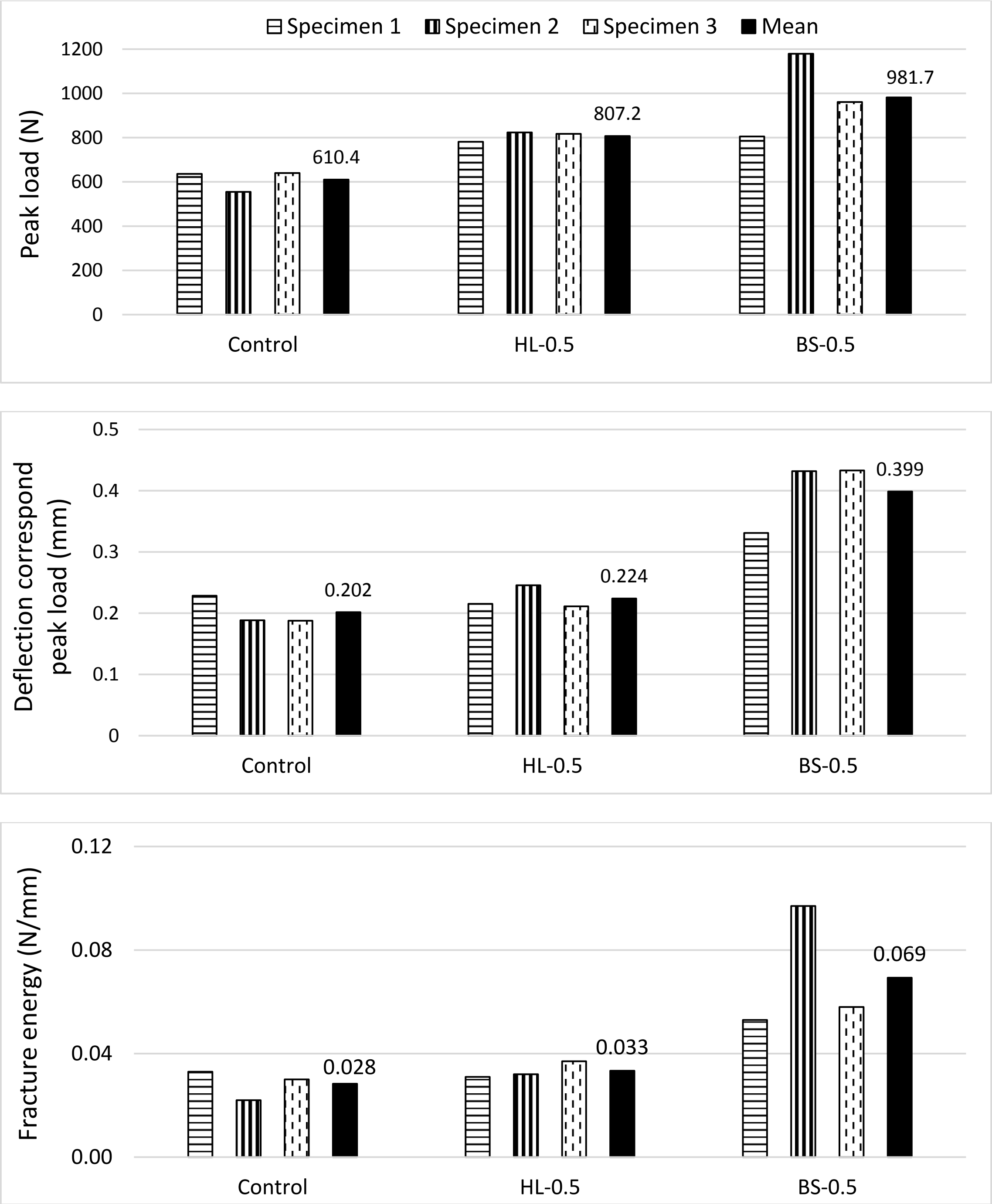

Fig. 12. Peak loads, deflections corresponding to peak loads and fracture energy of the mixtures.

3.4. Water absorption and sorptivity

Water absorption and coefficient of sorptivity of the mixtures are given in Figs. 13 and 14, respectively. Water absorption increased by 12% and 4.8% with the inclusion of hemp and basalt fibers, respectively. The fact is probably due to the reduced workability with the addition of fibers. In addition, hemp fiber also absorbs water due to its porous structure. The addition of basalt fiber did not have a significant effect on the water absorption capacity. Nevertheless, hemp fiber-reinforced specimens had the highest water absorption capacity. However, fiber inclusion reduced the coefficient of sorptivity by 20% and 55% for hemp and basalt fiber, respectively. Wang et al. (2021) marked that the addition of fiber to face slab concrete increased the total porosity and fraction of larger pores, but reduced the fraction of smaller pores. In this study the effect of basalt and hemp fibers on the capillary water absorption was clearly seen. The increase in water absorption and decrease in coefficient of sorptivity suggested that the addition of fiber changed the pore structure of the cement mortar. It is thought that with the inclusion of fibers, the fraction of larger pores (arisen from insufficient compactibility and responsible for water absorption) increased, however, the amount of smaller pores (arisen from crack treatment effect of fibers and responsible for sorptivity) reduced.

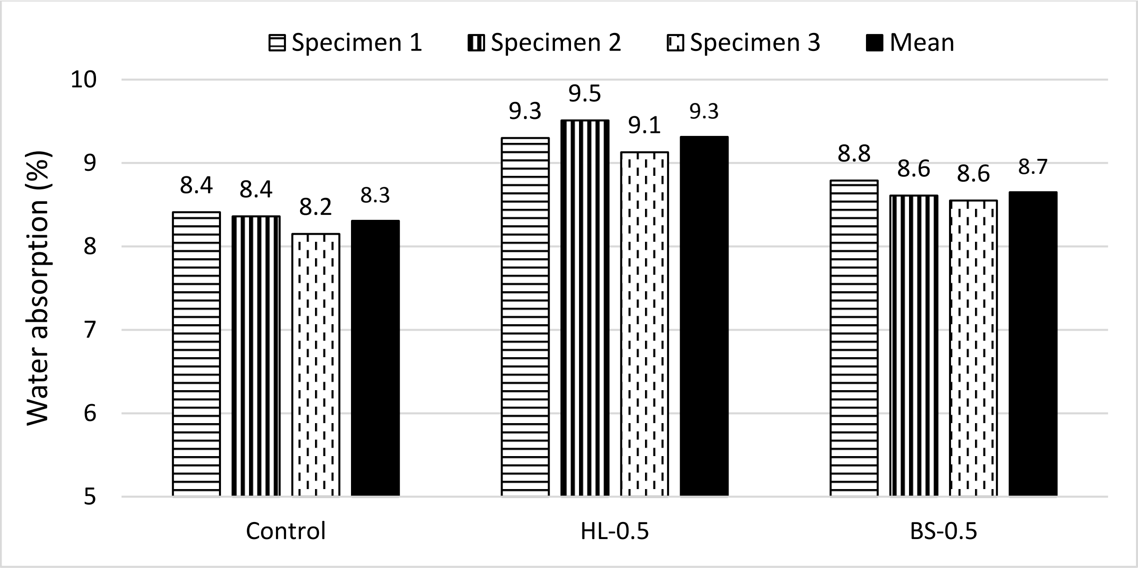

Fig. 13. Water absorption values.

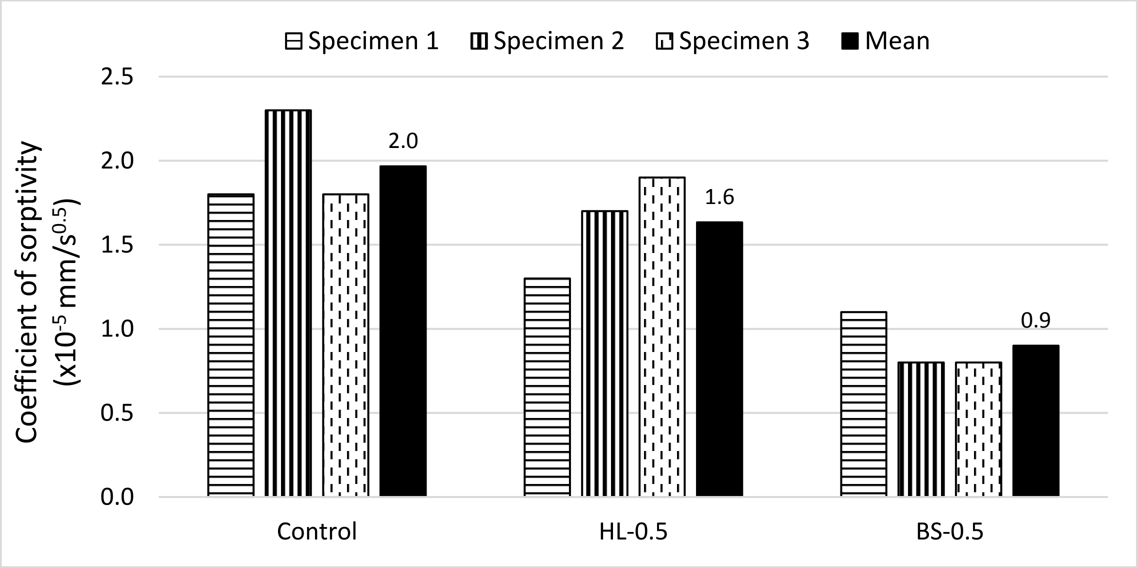

Fig. 14. Coefficient of sorptivity values.

4. Conclusions

This study investigated the effects of inclusion of hemp and basalt fibers on the fresh properties, mechanical strength and fracture energy of fiber-reinforced cement-based composites. For the materials used and tests applied, the following conclusions may be drawn:

- With the inclusion of fiber, mortar flow diameters decreased, and the fact became clearer at higher fiber dosages. As a result of the decreased workability (compactibility) with fiber inclusion, the unit weight of composites decreased progressively. In this regard, the negative effect of basalt fiber addition on flow diameter was higher than that of the hemp fiber.
- The effect of fibers on flexural strength was negligible at lower dosages (0.125 and 0.25%). In terms of flexural strength, the optimum fiber dosage was 0.5%. It was possible to increase flexural strength up to 10.7% and 19.6% with hemp and basalt fiber addition, respectively. Unlike flexural strength, fibers decreased the compressive strength. However, the reduction in compressive strength was negligible in the low dosage basalt fiber-bearing mixtures.
- Fibers enhanced the peak load, the deflections corresponding to the peak loads and fracture energy of the mixtures. From fracture energy viewpoint, positive effect of the basalt fiber was more than that of the hemp fiber. The fracture energy of hemp and basalt fiber-reinforced composites was higher than that of fiber-free mixture by 17.9% and 146.4%, respectively.
- Hemp and basalt fiber inclusion reduced the coefficient of sorptivity by 20% and 55%, respectively. However, the water absorption of fiber-reinforced composites was higher than that of the plain mixture. This probably occurred due to the change in the pore structure.

Author Contributions

The sole author made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; was involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Acknowledgements

None declared.

Funding

The author received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

Abbas YM, Khan MI (2016). Fiber–matrix interactions in fiber-reinforced concrete: A review. *Arabian Journal for Science and Engineering*, 41, 1183-1198.

Abdalla JA, Thomas BS, Hawileh RA (2022). Use of hemp, kenaf and bamboo natural fiber in cement-based concrete. *Materials Today: Proceedings*, 65, 2070-2072.

Ahmad J, Zhou Z (2022). Mechanical properties of natural as well as synthetic fiber reinforced concrete: a review. *Construction and Building Materials*, 333, 127353.

Al-Rousan ET, Khalid HR, Rahman MK (2023). Fresh, mechanical, and durability properties of basalt fiber-reinforced concrete (BFRC): a review. *Developments in the Built Environment*, 14, 100155.

Arslan ME (2016). Effects of basalt and glass chopped fibers addition on fracture energy and mechanical properties of ordinary concrete: CMOD measurement. *Construction and Building Materials*, 114, 383-391.

ASTM C348-21 (2021). Standard test method for flexural strength of hydraulic-cement mortars. American Society for Testing and Materials, PA, USA.

ASTM C349-18 (2018). Standard test method for compressive strength of hydraulic-cement mortars (using portions of prisms broken in flexure). American Society for Testing and Materials, PA, USA.

ASTM C1437-20 (2020). Standard test method for flow of hydraulic cement mortar. American Society for Testing and Materials, PA, USA.

ASTM C1585-20 (2020). Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. American Society for Testing and Materials, PA, USA.

Bencardino F, Rizzuti L, Spadea G, Swamy RN (2010). Experimental evaluation of fiber reinforced concrete fracture properties. *Composites Part B: Engineering*, 41, 17-24.

Chen M, Feng J, Cao Y, Zhang T (2023). Synergetic effects of hybrid steel and recycled tyre polymer fibres on workability, mechanical strengths and toughness of concrete. *Construction and Building Materials*, 368, 130421.

Çomak B, Bideci A, Salli Bideci O (2018). Effects of hemp fibers on characteristics of cement based mortar. *Construction and Building Materials*, 169, 794-799.

El-Abbasy AA (2022). Production, behaviour and mechanical properties of ultra-high-performance fiber concrete - a comprehensive review. *Case Studies in Construction Materials*, 17, e01637.

Grubesa IN, Markovic B, Gojevic A, Brdaric J (2018). Effect of hemp fibers on fire resistance of concrete. *Construction and Building Materials*, 184, 473-484.

Gültekin A, Beycioğlu A, Arslan ME, Serdar AH, Dobiszewska M, Ramyar K (2022). Fresh properties and fracture energy of basalt and glass fiber–reinforced self-compacting concrete. *Journal of Materials in Civil Engineering*, 34(1).

Jianbing Y, Yufeng X, Saijie L, Zhiqiang X (2022). Experimental study on shear performance of basalt fiber concrete beams without web reinforcement. *Case Studies in Construction Materials*, 17, e01602.

Kabay N (2014). Abrasion resistance and fracture energy of concretes with basalt fiber. *Construction and Building Materials*, 50, 95-101.

Kaplan G, Bayraktar OY (2021). The effect of hemp fiber usage on the mechanical and physical properties of cement based mortars. *Research on Engineering Structures and Materials*, 7(2), 245-258.

Kizilkanat AB, Kabay N, Akyüncü V, Chowdhury S, Akça AH (2015). Mechanical properties and fracture behavior of basalt and glass fiber reinforced concrete: An experimental study. *Construction and Building Materials*, 100, 218-224.

Li Z, Shen A, Zeng G, Chen Z, Guo Y (2022). Research progress on properties of basalt fiber-reinforced cement concrete. *Materials Today Communications*, 33, 104824.

Li Z, Wang X, Wang L (2006). Properties of hemp fibre reinforced concrete composites. *Composites Part A: Applied Science and Manufacturing*, 37, 497-505.

Rilem (50-FMC) 1985 Determination of the fracture energy of mortar and concrete by means of three - point bend tests on notched beams. *Materials and Structures*, 18, 287-290.

Ruano G, Bellomo F, Lopez G, Bertuzzi A, Nallim L, Oller S (2020). Mechanical behaviour of cementitious composites reinforced with bagasse and hemp fibers. *Construction and Building Materials*, 240, 117856.

Şahan MF, Öncel FA, Ünsal İ (2021). Effect of fiber ratio on the impact behavior of polypropylene fiber reinforced samples. *Journal of Structural Engineering & Applied Mechanics*, 4(4), 239-248.

Stevulova N, Kidalova L, Terpakova E, Junak J (2022). Utilization of hemp concrete as building material. Visions for the Future of Housing: Mega Cities. *Proceedings of the 38th IAHS World Congress*, İstanbul, Türkiye, 358-364.

Suardana NPG, Piao Y, Lim JK (2011). Mechanical properties of hemp fibers and hemp/pp composites: effects of chemical surface treatment. *Materials Physics and Mechanics*, 11, 1-8.

Sullins T, Pillay S, Komus A, Ning H (2017). Hemp fiber reinforced polypropylene composites: the effects of material treatments. *Composites Part B: Engineering*, 114, 15e22.

TS EN 196-1 (2016). Methods of testing cement - part 1: determination of strength. Turkish Standards Institution, Ankara, Türkiye.

Uygunoğlu T, Topçu IB, Şimşek B, Eryeşil Ö, Al-Turki YAYA (2022). Çimento esaslı harçların fiziksel ve mekanik özeliklerinde polivinil alkol (PVA) liflerin etkisi. *Politeknik Dergisi*, 25(1), 29-36.

Vairagade VS, Dhale SA (2023). Hybrid fibre reinforced concrete - a state of the art review. *Hybrid Advances*, 3, 100035.

Wang L, He T, Zhou Y, Tang S, Tan J, Liu Z, Su J (2021). The influence of fiber type and length on the cracking resistance, durability and pore structure of face slab concrete. *Construction and Building Materials*, 282, 122706.

Zhao Q, Yu J, Geng G, Jiang J, Liu X (2016). Effect of fiber types on creep behavior of concrete. *Construction and Building Materials*, 105, 416-422.

Zhou X, Saini H, Kastiukas G (2017). Engineering properties of treated natural hemp fiber-reinforced concrete. *Frontiers in Built Environment*, 3, 33.

Zhou Y, Zou S, Wen J, Zhang Y (2023). Study on the damage behavior and energy dissipation characteristics of basalt fiber concrete using SHPB device. *Construction and Building Materials*, 368, 130413.

CHALLENGE JOURNAL OF CONCRETE RESEARCH LETTERS 14 (4) (2023) 118–127

Challenge Journal of Concrete Research Letters

Review

An overview on the hazards and handling methods of construction and demolition wastes: Special focus on recycled concrete aggregates

Alhamza Derki [a], Pınar Akpınar [b,*]

[a] *Department of Civil Engineering, Near East University, Nicosia,Turkish Republic of Northern Cyprus*
[b] *Department of Civil Engineering, Bahçeşehir Cyprus University, Nicosia, Turkish Republic of Northern Cyprus*

ABSTRACT

With the demand increased in construction activities within the last century, several scientific research studies have been focusing on different aspects of construction and demolishing wastes, while considering the severity of environmental problems that they cause. This work presents the results of out an extensive literature survey in order to provide an overview on the hazards and handling methods of construction and demolishing wastes. Results of this literature review indicate that landfilling has been the most commonly used method, even though the recycling of the construction and demolishing wastes was found out to be the most environmentally-friendly solution. It was observed that groundwater and soil may be heavily affected by the leaching constituents of landfilled construction wastes. On the other hand, using these wastes in the form of recycled concrete aggregates was observed to eliminate these hazards. The results of literature survey pointed out that the use of demolished concrete wastes as recycled concrete aggregates could be widely adopted by construction sector only if the resulting concrete is of satisfactory quality. Hence, information on different quality aspects of concrete made of recycled concrete aggregates are presented systematically as a clear guide in this work, to verify its feasibility as an environment-friendly waste elimination method.

ARTICLE INFO

Article history:
Received 15 August 2023
Revised 25 October 2023
Accepted 7 December 2023

Keywords:
Construction and demolition wastes
Groundwater pollution
Soil pollution
Landfilling
Recycling
Recycled concrete aggregates

1. Introduction

The change in the life of modern society yielded various types of wastes that affect the nature in different scales if not managed adequately. Several studies in the previous literature had investigated the effects of varying wastes on the nature in general as well as on ground water specifically (Özkarova et al. 2019; Ahmed et al. 2019; Rezende et al. 2019). Besides numerous waste types and sources, construction and demolishing wastes have also observed to be increased as a direct result of the significant increase of population worldwide from 1.5 billion up to 7.5 billion within this century (Xiao 2018). The increase of world population leads to higher demand of certain types of structures made up with varying construction materials. This increase in the construction activities also lead to an increase in demolition processes; hence generation of higher quantities of construction and demolition (C&D) wastes has been inevitable. With its continuously increasing quantities, C&D wastes and their consequent environmental hazards has become a significant problem worldwide (Alakara et al. 2022).

In certain developing countries, C&D wastes can unfortunately be disposed even directly on the ground in a totally unregulated and uncontrolled manner. Fig. 1 illustrates such an inappropriate disposal of construction and demolition wastes that was done in a developing country, possibly in an illegal way; avoiding the control of local authorities.

Figs. 1(a-b) provide a common example and a visual evidence of the possible variety and the mixed nature of construction and demolishing wastes. This fact makes environmental problem caused by C&D wastes a complex one; requiring a thorough understanding of its components, and their individual effects on nature before concluding on the optimum way the manage them.

---

* *Corresponding author*. Tel.: +00-000-000-0000 ; E-mail address: pinar.akpinar@baucyprus.edu.tr (P. Akpınar)

ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2023.04.003

Fig. 1. Uncontrolled disposal of varying types of construction and demolition wastes in nature: (a) Plastics and tiles; (b) Asphalt and concrete.

1.1. Factors affecting C&D waste generation

Construction materials vary according to the countries that they are produced and to the construction traditions that they may have. In the USA, timber is a very conventional construction material; while in the UK for example, brick is used very widely. All construction materials have life cycle; first their raw materials are quarried from natural sources to in order to manufacture the exact construction material with the desired qualities to be used in the construction industry.

It is a matter of time until the structures made up of these produced construction materials have to be removed due to various reasons. Reaching the end of their designed lifetimes, any premature performance failure, or sometimes the demands to construct more modern structures could be the reasons for demolishing these structures and hence, construction and demolishing wastes are generated.

A noteworthy study published in 2023 presented the data on the estimated construction and demolishing wastes quantities worldwide and reported that EU generates more than 820 million of tons of annually (Soto-Paz et al., 2023). Among EU countries, France and Germany are observed to generate the highest C&D wastes quantities with the reported estimated values of 246 and 200 million of tons annually. Other significant waste quantities are reported for United States and China, being as 534 and 1130 million tons annually, respectively (Soto-Paz et al., 2023).

Additionally, numerous studies have been carried out previously in order to determine the type and the quantities produced by different countries. The results of these studies are for sure critical for the process of determining the optimum waste disposal and management methods, taking in to consideration of both environmental and economic aspects, that would cover the needs of the countries of concern (Martinez et al. 2010; Li et al. 2019).

In their study, Pellegrino and Faleschini (2016) have reported the annual construction and demolition waste quantities produced in various European countries with a remark on the year of their inclusion to European Union (EU). Their data indicated that the countries that have been included to EU at earlier ages are generating higher quantities of construction and demolishing wastes, when they are compared to other countries which have been included to EU more recently.

This finding could be due to the economic growth reached by elder European countries that might have reflected to their construction activities as well. However, it should be considered that the population of each country and hence, the total demand for construction activities, also are expected to play a great role on the exact quantity of the annual construction and demolition waste generation resulted.

Hence, each country may need to study the problem to a different extent; considering the type of waste generated and the total generated quantities of waste in order to determine the magnitude of the threat posed to their local environment, as well as the protective measurements and waste handling strategies.

1.2. C&D wastes as a source of hazardous materials

Previous studies focusing on the hazardous materials coming from construction and demolition wastes were observed to report leachate information mainly for a variety of mixed waste types such as; a mixture of concrete, asphalt, wood, plastic, glass, paintings, sealing agents etc. Hence, it is typical to see a list of concentration of these aforementioned elements together for a given waste case.

Previous studies report that construction and demolition wastes cause contamination by releasing hazardous materials such as heavy metals like Arsenic (As), Lead (Pb), Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Zinc (Zn), Calcium (Ca), Magnesium (Mg), And Antimony (Sb); Also, Chloride (Cl), Fluoride (F), Sulphate (SO4), and phenol (Galvin et al. 2012; Butera et al. 2014).

The related literature also reports regulations that specify the allowed concentration limits of these mentioned potentially hazardous materials in the landfill leachates (EU Council 2003). Exceeding these limits in such a case of waste disposal is regarded as a potential threat to environmental balances in general.

In general, a lack of detailed information on the individual leachate results for each type of wastes; that would serve to identify the exact impact of that type of waste only to environment. On the other hand, concrete which is a very popular construction material is observed to be studied with an additional focus in the related literature, unlike many other construction materials that may end up being wastes. In these specific studies, concrete leachate is reported to lead to release of various materials like chloride, sulphate, and mainly calcium hydroxide in the soil. The effects of calcium hydroxide and other concrete leachates on nature will be discussed in further detail in the following sections.

2. C&D Wastes Handling and Management Methods

Numerous studies have been carried out in order to determine the optimum C&D wastes management method within three commonly used C&D waste management methods. The commonly used methods for managing construction and demolishing wastes are known as landfilling, incineration, and recycling. The efficiency of the waste management methods was discussed in these studies based on criteria such as cost reduction for both transportation and raw materials, and reducing the impact of the construction and demolition wastes on the environment. Fundamental information about these three C&D waste handling methods are presented in the below subsections.

2.1. Landfilling as a handling method for C&D wastes and consequent hazards

This method could be considered as the simplest, but not necessarily the most efficient, method among others. Landfilling is a waste disposal method where wastes are buried within the ground. As the wastes seemingly disappear, this method became popular and widely used especially in certain countries.

Landfilling is done by initially excavating destination location and in the bottom of the cavity formed at that location leachate collecting mechanism installed, and then filling with waste and cover the cavity with installation of gas vent It is known that by landfilling method of waste management, the adverse impacts of waste leachate on environment cannot be avoided fully. Landfills are expected to be designed to not to have a negative impact on the surrounding environment; yet, they still do, as reported in studies (Malek and Shaaban 2018). Landfilling activities are known to cause negative effects especially on the quality of soil and groundwater. This impact is caused mainly by leaching of hazardous materials from landfilled materials such as concrete, asphalt, wood, gypsum drywalls that are common C&D wastes, yielding a source of heavy metals and other chemicals permeate to soil (Plaza et al. 2017; Saxe et al. 2007).

After construction and demolition wastes are disposed into landfills, they will be exposed to the certain surrounding environmental factors. Water presence and percolation mainly causes leachate of the waste compositions. When it rains the rainfall permeate through the cover layer of the landfill, reaching the debris beneath. Rainfall water will react with materials of the debris causing these materials to leach into soil and then carrying them to groundwater. Hence, groundwater, which is a vital source for human activities, would also be contaminated eventually with these hazardous materials. Evidently this would cause negative effects on drinking water sources, as well as on agricultural activities and on the obtained crop qualities (Di Palma and Mecozzi 2010; Powel et al. 2015).

In their work, Powel et al. (2015) studied the effect of leachate minerals from construction and demolition waste landfills from 91 landfilling sites in Florida, USA, which contained wood, concrete and gypsum drywalls, on the quality of up-gradient and downgradient groundwater. Results obtained from the analysis of samples collected semi-annually for 10 years from these landfill sites showed that various materials like dissolved solids of sulphate, chloride, iron, ammonia-nitrogen and aluminum exceeded allowed concentration limits in groundwater and therefore, posed a threat on the surrounding nature and human activities around.

A study in Algeria took place in order to assess the impact of demolition debris buried 5 years ago on the quality of groundwater. The soil beneath the landfilling site was Marly-Calcareous with permeability of (10^{-2} m sec^{-1} to around 10^{-6} m sec^{-1}). Analysis of leachate results from the landfill site showed high Chemical Oxygen Demand “COD” (1136 mg/L O^2) and Biological Oxygen Demand “BOD5” (200 mg/L O_2). COD is a parameter indicating the measure of pollutants in water and deleterious wastes in aqueous form (Hu and Grasso 2005). Higher quantities of COD detected in water is reported to lead further negative environmental impacts (Hach 2023). Being another importer water quality parameter, BOD is known to facilitate the assessment of the effect of discharged waste water on the environment exposed to the wastes (Real Tech 2017); hence, higher BOD implies increased effects on the environment. Furthermore, leachate in this mentioned study showed pH value of 7.65 with heavy metals concentrations beyond national limits except for Zinc (Zn). For groundwater, three wells in the parameter of the landfill were considered as piezometers. Analyzing of the quality of water in these piezometers showed a pH value of 6.88; while for heavy metals concentrations were acceptable except for Zinc (Zn) with (0.779 mg/L). Also, a bacterial contamination was found in the groundwater by total coliforms (1100/100 mL) (Benmenni and Bemrachedi 2010).

Construction and demolition wastes debris can also cause emission of hydrogen sulide H_2S sourced from gypsum drywalls debris. H_2S has a serious effect on public health including eyes problems as well as cases coma if one is exposed to high concentrations (Lim et al. 2016). When debris is exposed to water such as rain from environment surrounding landfill, calcium and sulphate are released. With no presence of free oxygen, sulphate-reducing bacteria produces hydrogen sulphide H_2S that is released into the surrounding atmosphere causing harmful effect on the surrounding environment and residents (Lim et al. 2016).

Buildings wastes occupy 20–40% of cities' waste, and carbon dioxide emissions produced were 7% of the total CO_2 emissions which has a major role in global warming (Xiao 2018).

Debris leachate causes mobilization of various metals such as iron, manganese, nickel, and arsenic could lead to change of characterizations of soil due to alteration of the equilibrium within. Furthermore, metals could mobilize from soil to groundwater in the surrounding environment of a construction and demolition waste landfill. Metal mobilization is toxic and causes soil to be unsuitable for agricultural activities.

Also, when groundwater shows high concentrations of hazardous metals, this causes serious problems to public health and agricultural activities depending on such water sources (Di Palma and Mecozzi 2010; Wang et al. 2012; Hartwich and Vollpracht 2017).

A six-months study on C&D wastes landfills was made by Weber et al. (Weber et al.2002), which reported concentrations of soluble ions in the leachate like calcium and sulphate were predominant ions. Also, for heavy metals, it was showed that metals like arsenic, aluminum, copper, manganese, and iron were found. Arsenic concentrations exceeded the primary water quality limits. The greater impact in the secondary standards was recorded by manganese followed by iron, concluding that the problem is that generally C&D wastes landfills are unlined, unlike Municipal Solid Waste "MSW" landfills.

Moreover, when construction and demolition waste debris containing masonry and partially carbonated concrete, it was reported to have leaching of sulphate and chlorides, which have an effect on pH level of the soil and groundwater in the surrounding environment. This variation of pH level also leads to deplete agricultural properties of soil and properties of groundwater since plant roots cannot live in high or low pH levels and groundwater will not be drinkable by surrounding settlements residents depending on such water source (Galvin et al. 2012; Butera 2014). Furthermore, uranium could naturally occur in the environment and with presence of certain ions from leachate of construction and demolition wastes depending on the source materials like type of aggregates used such as granite. Uranium can mobilize into groundwater in elevated concentrations that leads to harmful health effects compared to other leachate material elevated concentration (Letman 2018).

A study prepared by Minnesota Pollution Control Agency showed a high concentration for both human and environmental standards of heavy metals like Arsenic, Boron, and Manganese. These three metals come mainly from concrete, steel reinforcement, and Chromated Copper Arsenate "CCA" treated wood (Chiles 2019).

Zhang et al. (2017) studied arsenic leaching tendency and effects in construction and demolishing debris landfills and the relation it has with the content of gypsum drywall within the wastes. This study reported that with the increase of sulfides up to a certain threshold value, the arsenic concentrations detected were decreasing and after that threshold value, even though the sulfides kept increasing the previously decreasing arsenic concentration started to exhibit an increasing trend (Zhang et al. 2017).

On the contrary, a study about landfilling of arsenic treated wood wastes in various C&D wastes unlined landfills and its impact on groundwater quality in Florida, USA. Results of the study showed that there is no evidence of hazardous mobilizing of arsenic into groundwater. This study suggested that the limited mobilization of arsenic could be due to the soil characteristics. Also, insolubility of wood as they are usually dumped in large pieces that makes the exposed surface for leachate is lower (Saxe 2007).

Another study stated the effect of diversion of wastes from construction and demolition activities on the surrounding environment including groundwater quality. Also showing that by applying C&D wastes diversion techniques, the impact on the surrounding environment and contaminating of groundwater will be reduced. Furthermore, applying C&D wastes diversion techniques has an economical effect by reducing the costs of handling and transportation, as well as avoiding regulatory issues, creating markets, with preservation of non-renewable virgin materials (Smith and Bishop 2005).

Undoubtedly demolished concrete is one of the most commonly found source of C&D wastes too. Previous studies point out calcium hydroxide as one of the major leachates of waste concrete affecting ground water and soil negatively. Calcium hydroxide yields in high alkalinity; hence more calcium hydroxide concentration in landfill surrounding soil will lead to higher pH value; which has negative effect on the vegetation existence and hence the animal existence. Furthermore, calcium hydroxide leachate can reach the groundwater which will also leads to increase the pH level that will affect the quality of groundwater (Hartwich and Vollpract 2017).

The information gathered from the previous studies clearly indicate that leachate from construction and demolition waste landfills leads to mobilization of heavy metals and other hazardous materials into soil and eventually into both surface and groundwater. Mobilization of these hazardous materials will negatively affect the vegetation cover hence the animals depending on these plants to survive. Furthermore, agricultural activities will also be negatively affected since they depend on water sources that will be contaminated with hazardous materials from nearby landfills that will eventually has an effect on public health and food supplies in agricultural communities.

Additionally, a recent study points out the increasing problem due to the scarcity of urban lands that could be for being used for landfilling (Chen et al. 2021). In this study, elimination of C&D wastes through sea filling has been defined as an emerging treatment method for wastes. However, the same study also states that there is lack of knowledge on the consequences of sea filling and therefore more research should be done on the environmental impacts of using sea filling treatment method for the elimination of C&D wastes (Chen et al. 2021).

2.2. Incineration as a handling method for C&D wastes

This method mainly consists of the action of burning wastes in facilities called "Combustors". It consists of two stages: the first stage is carried out with the initial burning "Chamber" (700°C) and then secondary burning "Grate" (980-1090°C) is employed in the second stage. This method has high application and opportunity costs with toxic pollutants emissions and high waste of energy and it is also applied to combustible wastes only. On the other hand, this method leads to reduce volume of wastes by 95% and mass by more than 85%, and in the case of being equipped properly, they can work as energy generators. Also, this method is known to require less space than it is required by landfills and it is reported that soil and groundwater contamination can be prevented in this way (Kumar and Ankaram 2019).

However, it should be noted that the applicability of this handling method for construction and demolishing wastes remains limited. Only some types of C&D wastes could be eliminated by incineration. Timber and certain types of plastics could be counted in incinerable category, where demolished concrete as well as bricks and tiles could not be eliminated directly with this technique (Rhyner 1998; Küçükvar et al. 2014)

2.3. Recycling as a handling method for C&D wastes: Special focus on recycled concrete aggregates application

A common way of recycling method used for construction and demolishing wastes is through reusing them as "recycled concrete aggregates" in the manufacture of new concrete elements. This method is known to reduce the cost and unlike landfilling and incineration, recycling has no harmful impact on the environment

Results obtained in the surveyed previous research studies have shown that recycling method for managing the construction and demolition wastes is the optimum method in cases of cost reduction, reducing environmental impact, and preserving raw materials (Ortiz et al. 2010; Marzouk and Azab 2014; Ulubeyli et al. 2017; Galvez-Martos et al. 2018; Shafiqul Islam et al. 2018; Abdeltawab-Abuellella and Elmalky 2023).

Wastes from demolished concrete buildings can be re-used in the form of recycled concrete aggregates (RCA). For this purpose, the demolished concrete elements are crushed into smaller fractions, separated from other undesired contaminations and added in to new concrete mixtures as a replacement to natural aggregates. In this way, the use of natural (i.e. quarried) aggregates can me decreased, supporting the protection of natural resources as well.

Fig. 2 illustrates summarized information about the life cycle of concrete as a construction material and regaining construction and demolishing wastes as recycled concrete aggregates. C&D waste treatment plants can be fixed or mobile, depending on the required services. Both types of treatment plants can receive and process all types of construction and demolition wastes.

Fixed treatment plants can process higher amounts of debris than mobile plants. However, they have some disadvantages such as their need to be installed in authorized closed areas; hence, debris transportation costs might become an issue since the fixed plants could be located far from the demolition site.

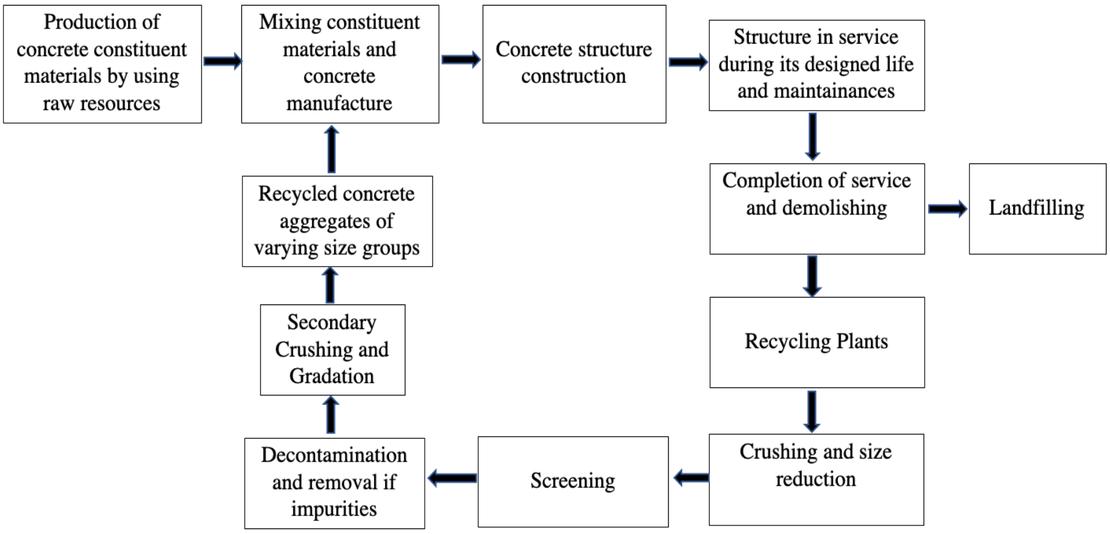

Fig. 2. Concrete life cycle and recycling.

Mobile treatment plants have the advantage of relocation ability; that can process debris directly onsite without needing extra transportation cost of debris.

On the other hand, they have lower rate of debris processing, since they are usually smaller than fixed treatment plants and they need extra labor for reinstalling on each desired site. In any case, general steps followed by both types of plants are very similar (Pellegrino and Faleschini 2016) and are as listed below:

- Crushing
- Separation of ferrous elements
- Screening
- Decontamination and removal of impurities (e.g. soil, glass, plastic, etc.)

Countries investing in recycling are mostly developed countries and the quantities of concrete recycling vary from one country to another (Tam et al. 2018).

A crushed old concrete fraction that is going to be used as RCA, involves the old and damaged mortar from the old concrete attached to old natural aggregates. The porous and damaged character of the old adhered mortar within RCA is reported to be likely to yield some adverse effects on the performance of the new concrete to be manufactured (Juan and Gutierrez. The extent of the negative effects of adhered mortar within recycled concrete aggregates, determines the success of RCA use in new concrete and the general feasibility of its application as a sustainable environmentally friendly waste elimination method.

3. Viability of RCA Use for New Concrete Manufacture as an Environmentally-Friendly Waste Elimination Method

Elimination of C&D wastes in an environmentally friendly way by converting them into a concrete constituent material only could be widely accepted and sustainable if new concrete mixes containing RCA can meet the performance criteria required for engineering applications. In general, concrete's mechanical properties and quality is known to depend greatly on the type and quantity of cementitious materials water and aggregates that are used (Akpinar and Khashman 2017; Khashman and Akpinar 2017; Al-Gburi et al. 2022). Hence, if the quality of the RCA and the performance of the new concrete containing it are monitored in detail, then the potential performance problems are suggested to be overcome by taking necessary concrete mix design precautions (Paul 2017).

Properties of both fresh and hardened concrete mixes containing recycled concrete aggregates, and their durability characteristics have been investigated by numerous researchers in order to evaluate their performance in comparison with conventional concrete mixes. A summary of these investigated concrete characteristics and the regarding performance of RCA-containing concrete mixes are presented in Tables 1 and 2, by providing the references of the previous research works encountered in the related literature.

These previous works provide detailed information on the experimental procedures that they have used in order to provide insights on the concepts selected concrete characteristics that they have focused. The codes and standard procedures that they have followed for material and sample preparations, as well as the test methods used for each parameter of interest varied in certain cases; however, their main findings about the concrete characteristics mentioned in given Tables 1 and 2 were observed to be in harmony. Bar charts presented in Fig. 3 have been prepared based on the experimental data presented in the references mentioned in these tables.

Table 1. RCA-containing concrete properties in comparison with conventional concrete.

Concrete characteristics	Performance of RCA-containing concrete	References presenting supporting experimental evidence
Compressive strength	Lower compressive strength	(Wang et al. 2012; Duan and Poon 2014; Paul 2017; Abdel-Hay 2017; Bulatovic et al. 2017; Pedro et al. 2017; Dimitriu et al. 2018; Gonzalez-Fonteboa et al. 2018; Hao et al. 2018; Hayles et al. 2018; Rao et al. 2018; Sharkawi et al. 2018)
Splitting tensile strength	Lower split tensile strength	(Thomas et al. 2013; Duan and Poon 2014; Pedro et al. 2017; Gonzalez-Fonteboa et al. 2018; Hao et al. 2018; Thomas et al. 2018; Akhtar and Sarmah 2018; Dimitriu et al. 2018)
Elastic modulus	Lower elasticity	(Thomas et al. 2013; Qi et al. 2017; Gonzalez-Fonteboa et al. 2018; Hao et al. 2018; Thomas et al. 2018; Amorim Junior et al. 2018)
Workability	Lower workability	(Abdel-Hay 2017; Hayles et al. 2018; Thomas et al. 2018; Pedro et al. 2018; Bravo et al. 2018; Dimitriou et al. 2018)
Permeability	Higher permeability	(Thomas et al. 2013; Xuan et al. 2017; Gonzalez-Fonteboa et al. 2018; Thomas et al. 2018; Guo et al. 2018; Pedro et al. 2018)

Table 2. Response of RCA-containing concretes to durability problems in comparison with conventional.

Durability problem	Response of RCA-containing concrete	References presenting supporting experimental evidence
Freeze and thaw	Higher deteriorations Higher ice expansions	(Pedro et al. 2017; Gonzalez-Fonteboa et al. 2018; Hao et al. 2018; Amorim Junior et al. 2018; Guo et al. 2018)
Alkali aggregate reaction	Higher reactivity Higher expansions	(Johnson and Shehata 2016; Delobel et al. 2016; Gonzalez-Fonteboa et al. 2018; Beauchemin et al. 2018
Carbonation	Higher carbonation rate	(Thomas et al. 2013; Pedro et al. 2017; Gonzalez-Fonteboa et al. 2018; Bravo et al. 2018; Guo et al. 2018)
Chloride attack	Higher chloride penetration	(Duan and Poon 2014; Ismail et al. 2017; Xuan et al. 2017; Pedro et al. 2018; Gonzalez-Fonteboa et al. 2018; Hao et al. 2018; Thomas et al. 2018; Akhtar and Sarmah 2018; Qi et al. 2017)
Sulphate attack	Higher expansions	(Pedro et al. 2017; Xuan et al. 2017; Bravo et al. 2018; Guo et al. 2018)
	Higher deterioration	(Gonzalez-Fonteboa et al. 2018; Rao et al. 2018)
Abrasion resistance	Similar to conventional concrete up to 50% replacement	(Pedro et al. 2017; Gonzalez-Fonteboa et al. 2018)

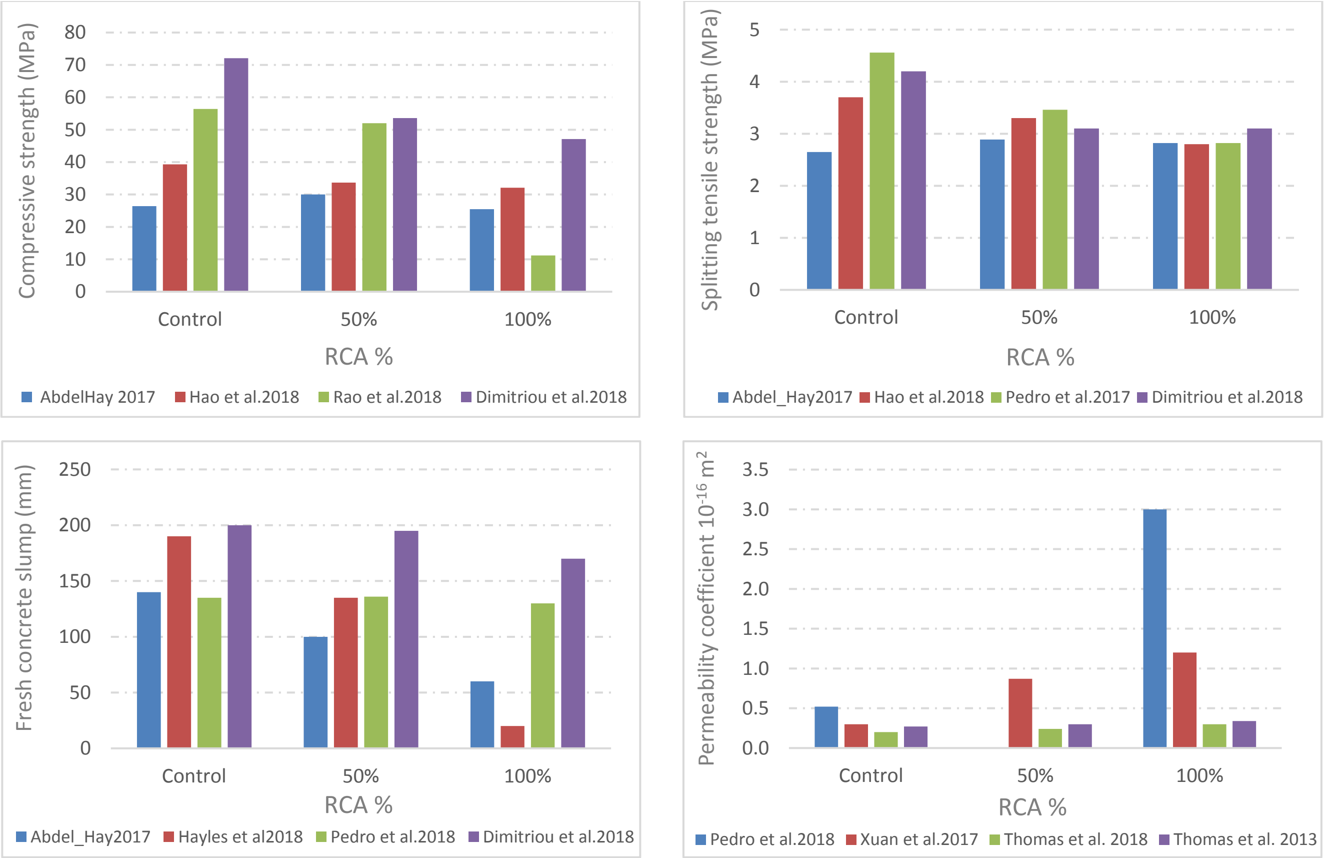

Fig. 3. Effect of % RCA inclusion on concrete properties:
(a) Effects on compressive strength; (b) Effects on splitting tensile strength;
(c) Effects on slump; (d) Effects on permeability coefficient.

Figs. 3(a) ad (3b) demonstrate the effect of %RCA inclusion on compressive and split tensile strength development (28-days) of concrete mixtures. Bars of each color represents concrete mixture results at a particular research study. Reported 50% and 100% RCA inclusions in comparison with the control mixtures in corresponding studies are demonstrated in each bar chart. When bars of each mix (of each study) is compared with respect to increasing percentage of RCA inclusion, it is observed that increased RCA contents yielded lower strength values. One should keep in mind that comparing strength values of the same RCA% from different studies could be complex, since each study had used different mix design parameters including w/c, cement contents, aggregate contents and so on, in addition to employing different cement types selected for their own studies. Fig. 3(c) demonstrates that the increase in the RCA inclusion yielded decreasing tendencies in the observed slump values. Part indicates that the increase in RCA content of the concrete mixtures yielded higher permeability coefficient of the samples.

RCA particles are produced from old and damaged and hence demolished building wastes. Each RCA particle includes traces of old aggregates as well as old mortar adhering it, both coming from the old and demolished concrete. Hence, these particles are known to be deteriorated as well; they might have defects and micro-cracks (especially within the old mortar within RCA) due to aging. Hence, they are known to possess lower quality compared to natural aggregates. All these drawbacks of RCA particles' quality affect the strength performance of the new concrete mixture that they are used within as well. RCA particles are also known to possess lower density, higher porosity and higher absorption in general. These would yield more water demand and reduced slump (if water content in the mix is constant). These qualities of RCA particles also are known to yield higher permeability tendencies in concrete mixtures if additional measures, such as increasing the cement and mineral additive content in the mix, are not taken (Derki 2019; Tayeh et al. 2020; Akpinar and Al-Attar 2021; Wang et al. 2021; Wang et al. 2023). All these characteristics and tendencies reported in the related literature are in parallel with the demonstrated tendencies in Fig. 3. More detailed discussions on the exact mechanisms that yielded the observed behaviors that are presented in parts a, b, c and d of Figure 3 are presented in the corresponding references cited in Table 1 and Fig. 3, considering the test set ups and specific materials and mix designs employed in each case of RCA use in concrete mixtures.

At a first glance, information presented in Tables 1 and 2, as well as in Fig. 3, might imply that RCA-containing concrete happens to possess definitively a lower quality when mechanical characteristics and its durability performance are compared to conventional concrete made only with natural aggregates. However, the continuing advancements in construction sector and the availability of various possibilities regarding the concrete additives and admixtures that can be included to concrete mixtures supplementary through a careful concrete mixture design process, enable the engineers to manufacture RCA-containing concretes with improved properties that are suitable for structural purposes (Xuan et al. 2017; Wang et al. 2017; Dimitriu at al. 2018; Akpinar and Al-Attar 2021).

Addition of pozzolanic materials such as silica fume, fly ash and blast-furnace slag, as cement additives, as well as using concrete admixtures such as superplasticizers have been reported to increase concrete density, compressive and flexural strength behaviour of RCA-containing concretes (Xuan et al. 2017; Guo et al. 2018 Thomas et al. 2018; Gonzalez-Fonteboa et al. 2018). Using such additives and admixtures were also reported to enhance impermeability of concrete and hence the durability characteristics of the concrete buildings in the cases where RCA was used (Chahal 2013; Pedro et al. 2018; Muhammedemin 2018; Derki 2019). In this way, the use of RCA in concrete manufacture can still be considered as a potentially effective method of elimination of C&D wastes, besides being an environmentally-friendly solution, minimizing the hazardous effects of these wastes on nature.

4. Conclusions

Conclusive remarks attained as the result of literature review carried out on more than sixty studies on the construction and demolishing wastes' characteristics, their impacts on groundwater and environmental, as well as their handling methods are presented below:

- The total quantity and the type of the construction and demolishing wastes generated by each country are determined by factors such as; their level of economic growth, population, total demand in construction activities and on the type of conventional construction materials that they use.
- Landfilling is reviewed as a widely used waste management method; however, leachate of hazardous materials from the landfilled wastes cannot be eliminated or kept under control fully.
- When landfilled, mixed types of construction and demolishing wastes have reported to cause leachate of potentially hazardous materials including heavy metals like arsenic, lead, cadmium, chromium, copper, mercury, nickel, zinc, calcium, magnesium, antimony, chloride, fluoride, sulphate and phenol that directly affects both soil and groundwater. International associations have been observed to make positive attempts to provide guiding information on the allowable concentration limits of these reported potentially hazardous materials.
- The listed leachates were observed to exceed the defined healthy limits in numerous studies. As a result, bacterial contaminations, highly toxic effects and severe pH changes in groundwater were reported. Consequently, these highly hazardous effects on groundwater were reported to be reflected on soil, agricultural activities, vegetation and animal life, besides its direct implications on potable water that is vital for human life.
- A lack of systematic information was observed on the surveyed literature regarding on the exact type of hazardous material likely to leach from each individual type of construction and demolition waste, since majority of the studies handled always mixed types of wastes.
- Being one of the most commonly used construction materials, concrete wastes effects on nature have been observed to be reported more insightfully within the surveyed previous studies. Results of these studies reported that leachate of calcium hydroxide from concrete and cement mortars mainly affects the pH level of soil and ground water and this causes negative effects on the natural vegetation, agricultural soil's quality and the on the quality of the groundwater resources.
- Recycling is reviewed as the most environmental-friendly waste management solution by the majority of the surveyed studies.
- Re-using demolished concrete wastes in the form of recycled concrete aggregates to be used in manufacture of new concretes is regarded as an effective solution for the problem of construction and demolishing wastes' elimination from nature.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

Abdel-Hay AS (2017). Properties of recycled concrete aggregate under different curing conditions. *HBRC Journal*, 13(3), 271–276.

Abdeltawab Abuellella A, Elmalky A (2023). Use of crushed bricks and recycled concrete as replacement for fine and coarse aggregates for sustainable concrete production. *Challenge Journal of Concrete Research Letters*, 14 (2), 39–46.

Ahmed S, Khurshid S, Qureshi F, Hussain A, Bhattacharya A (2019). Heavy metals and geo-accumulation index development for groundwater of Mathura City, Uttar Pradesh. *Desalination and Water Treatment*, 138, 291–300.

Akhtar A, Sarmah AK (2018). Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *Journal of Cleaner Production*, 186, 262–281.

Akpinar P, Khashman A (2017). Intelligent classification system for concrete compressive strength. *Procedia Computer Science*, 120, 712–718.

Akpinar, P., Al-Attar, H (2021). A case study on the viability of using increased quantities of recycled concrete aggregates in structural concrete for extending environmental conservation in North Cyprus. *Environmental Earth Sciences,* 80, 367.

Alakara EH, Sevim Ö, Demir İ, Günel G (2022). Effect of waste concrete powder on slag-based sustainable geopolymer composite mortars. *Challenge Journal of Concrete Research Letters*, 13(3), 101–106

Al-Gburi SNA, Akpinar P, Helwan A (2022). Machine learning in concrete's strength prediction. *Computers and Concrete*, 29(6) 433-444.

Amorim Júnior NS, Silva GAO, Ribeiro DV (2018). Effects of the incorporation of recycled aggregate in the durability of the concrete submitted to freeze-thaw cycles. *Construction and Building Materials*, 161, 723–730.

Beauchemin S, Fournier B, Duchesne J (2018). Evaluation of the concrete prisms test method for assessing the potential alkali-aggregate reactivity of recycled concrete aggregates. *Cement and Concrete Research*, 104, 25–36.

Benmenni MS, Benrachedi K (2010). Impact of earthquake demolition debris on the quality of groundwater. *American Journal of Applied Sciences*, 7(4), 545–550.

Bravo M, De Brito J, Evangelista L, Pacheco J (2018). Durability and shrinkage of concrete with CDW as recycled aggregates: Benefits from superplasticizer's incorporation and influence of CDW composition. *Construction and Building Materials*, 168, 818–830.

Bulatović V, Melešev M, Radeka M, Radonjanin V, Lukić I (2017.) Evaluation of sulfate resistance of concrete with recycled and natural aggregates. *Construction and Building Materials*, 152, 614–631.

Butera S, Christensen TH, Astrup TF (2014). Composition and leaching of construction and demolition waste: Inorganic elements and organic compounds. *Journal of Hazardous Materials*, 276, 302–311.

Chahal N, Siddique R (2013). Permeation properties of concrete made with fly ash and silica fume: Influence of ureolytic bacteria. *Construction and Building Materials*, 49, 161–174.

Chen K, Wang J, Yu B, Wu H, Zhang J (2021). Critical evaluation of construction and demolition waste and associated environmental impacts: A scientometric analysis. *Journal of Cleaner Production*, 287, 125071.

Chiles J, Hokenson A, Monaco B (2019). Groundwater impacts of unlined construction and demolition debris landfilling. Minnesota pollution control agency, Minnisota, USA, No. w-sw5-54a.

Delobel F, Bulteel D, Mechling JM, Lecomte A, Cyr M, Rémond S (2016). Application of ASR tests to recycled concrete aggregates: Influence of water absorption. *Construction and Building Materials*, 124, 714–721.

Derki A (2019). Experimental investigations on performance of recycled concrete aggregates-containing concrete exposed to heating-cooling cycles. *M.Sc. Thesis*, Near East University, Nicosia, Turkish Republic of Northern Cyprus.

Di Palma L, Mecozzi R (2010). Batch and column tests of metal mobilization in soil impacted by landfill leachate. *Waste Management*, 30(8–9), 1594–1599.

Dimitriou G, Savva P, Petrou MF (2018). Enhancing mechanical and durability properties of recycled aggregate concrete. *Construction and Building Materials*, 158, 228–235.

Duan ZH, Poon CS (2014). Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars. *Materials & Design*, 58, 19–29.

EU council decision- 2003/33/EC (2003). Council Decision 2003/33/EC establishing criteria and procedures for the acceptance of waste at landfills pursuant to article 16 of and Annex II to Directive 1999/31/EC. Official Journal of the European Communities, 2003/33/EC.

Gálvez-Martos JL, Styles D, Schoenberger H, Zeschmar-Lahl B (2018). Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling*, 136, 166–178.

Galvín AP, Ayuso J, Jiménez JR, Agrela F (2012). Comparison of batch leaching tests and influence of pH on the release of metals from construction and demolition wastes. *Waste Management*, 32(1), 88–95.

González-Fonteboa B, Seara-Paz S, De Brito J, González-Taboada I, Martínez-Abella F, Vasco-Silva R (2018). Recycled concrete with coarse recycled aggregate. An overview and analysis. *Materiales de Construcción*, 68(330), 151.

Guo H, Shi C, Guan X, Zhu J, Ding Y, Ling T, Wang Y (2018). Durability of recycled aggregate concrete – A review. *Cement and Concrete Composites*, 89, 251–259.

Hach (2023). Technical information on Chemical Oxygen Demand. Retrieved from: https://www.hach.com/parameters/chemical-oxygen-demand

Hao L, Liu Y, Wang W, Zhang J, Zhang Y (2018). Effect of salty freeze-thaw cycles on durability of thermal insulation concrete with recycled aggregates. *Construction and Building Materials*, 189, 478–486.

Hartwich P, Vollpracht A (2017). Influence of leachate composition on the leaching behaviour of concrete. *Cement and Concrete Research*, 100423–434.

Hayles M, Sanchez LFM, Noël M (2018). Eco-efficient low cement recycled concrete aggregate mixtures for structural applications. *Construction and Building Materials*, 169, 724–732.

Hu Z, Grasso D (2005). Water Analysis- Chemical Oxygen Demand. Encyclopedia of Analytical Science (2nd Ed.) pp.325-330.

Ismail S, Kwan WH, Ramli M (2017). Mechanical strength and durability properties of concrete containing treated recycled concrete aggregates under different curing conditions. *Construction and Building Materials*, 155, 296–306.

Johnson R, Shehata MH (2016). The efficacy of accelerated test methods to evaluate Alkali Silica Reactivity of Recycled Concrete Aggregates. *Construction and Building Materials*, 112, 518–528.

Juan MS, Gutiérrez PA (2009). Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction and Building Materials*, 23(2), 872–877.

Khashman A, Akpinar P (2017). Non-destructive prediction of concrete compressive strength using neural networks. *Procedia Computer Science*, 108, 2358–2362.

Küçükvar M, Egilmez G, and Tatari O (2014). Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life-cycle analysis: *Waste Management & Research*. 32(6), 500-508.

Kumar S, Ankaram S (2019). Waste-to-Energy Model/Tool Presentation. *In S. Kumar, R. Kumar, & A. Pandey (Eds.), Current Developments in Biotechnology and Bioengineering*, 239–258.

Letman MM, Drage J, Ryan AM, Lake C, Jamieson R (2018). Development of a leaching procedure to assess the risk of uranium leaching due to construction and demolition waste disposal. *Waste Management,* 78, 144–150.

Li J, Zuo J, Wang G, He G, and Tam VWY (2019). Stakeholders' willingness to pay for the new construction and demolition waste landfill charge scheme in Shenzhen: a contingent valuation approach. *Sustainable Cities and Society*, 101663.

Lim E, Mbowe O, Lee ASW, Davis J (2016). Effect of environmental exposure to hydrogen sulfide on central nervous system and respiratory function: a systematic review of human studies. *International Journal of Occupational and Environmental Health*, 22(1), 80–90.

Malek MIA, Shaaban MG (2008). Landfill Common Method and Practices of Solid Waste Disposal in Malaysia, ISWA, Singapore, Vol. MYS100320081047, p. 12.

Martínez Lage I, Martínez Abella F, Herrero CV, Ordóñez JLP (2010). Estimation of the annual production and composition of C&D Debris in Galicia (Spain). *Waste Management*, 30(4), 636–645.

Marzouk M, Azab S (2014). Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics. *Resources, Conservation and Recycling*, 8241–49.

Muhammedemin H (2018). Experimental studies on structural Concrete manufacture with Recycled concrete aggregate aged In North Cyprus. *M.Sc. Thesis*, Near East University Nicosia, Turkish Republic of Northern Cyprus.

Ortiz O, Pasqualino JC, Castells F (2010). Environmental performance of construction waste: Comparing three scenarios from a case study in Catalonia, Spain. *Waste Management*, 30(4), 646–654.

Özkaraova EB, Kalin RM, Gkiouzepa S, Knapp CW (2019). Industrial and agricultural wastes as a potential biofilter media for groundwater nitrate remediation. *Desalination and Water Treatment*, 172, 330–343.

Paul SC (2017). Data on optimum recycle aggregate content in production of new structural concrete. *Data in Brief*, 15, 987–992.

Pedro D, De Brito J, Evangelista L (2017). Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: Mechanical, durability and long-term properties. *Construction and Building Materials*, 154, 294–309.

Pedro D, De Brito J, Evangelista L (2018). Durability performance of high-performance concrete made with recycled aggregates, fly ash and densified silica fume. *Cement and Concrete Composites*, 93, 63–74.

Pellegrino C, Faleschini F (2016). Recycled Aggregates for Concrete Production: State-of-the-Art. In Sustainability Improvements in the Concrete Industry. Cham: Springer International Publishing, 5–34.

Plaza C, Xu Q, Townsend T, Bitton G, Booth M (2007). Evaluation of alternative landfill cover soils for attenuating hydrogen sulfide from construction and demolition (C&D) debris landfills. *Journal of Environmental Management*, 84(3), 314–322.

Powell JT, Jain P, Smith J, Townsend TG, Tolaymat TM (2015). Does disposing of construction and demolition debris in unlined landfills impact groundwater quality? Evidence from 91 landfill sites in Florida. *Environmental Science & Technology*, 49(15), 9029–9036.

Qi B, Gao J, Chen F, Shen D (2017). Evaluation of the damage process of recycled aggregate concrete under sulfate attack and wetting-drying cycles. *Construction and Building Materials*, 138, 254–262.

Real Tech (2017). Technical Information on Biochemical Oxygen Demand. Retrieved from: https://realtechwater.com/parameters/biochemical-oxygen-demand/#:~:text=Biochemical%20oxygen%20demand%20%2F%20biological%20oxygen%20demand%20is,matter%20or%20%E2%80%9Cfood%E2%80%9D%20available%20for%20oxygen%20consuming%20bacteria.

Rezende D, Nishi L, Coldebella PF, Mantovani D, Soares PF, Valim Junior NC, Bergamasco R (2019). Evaluation of the groundwater quality and hydrogeochemistry characterization using multivariate statistics methods: case study of a hydrographic basin in Brazil. *Desalination and Water Treatment*, 161, 203–215.

Rao KJ, Keerthi K, Vasam S (2018). Acid resistance of quaternary blended recycled aggregate concrete. *Case Studies in Construction Materials*, 8423–433.

Rhyner CR (1998). The effects on waste reduction and recycling rates when different components of the waste stream are counted. *Resources, Conservation and Recycling*, 24(3–4), 349–361.

Saxe JK, Wannamaker EJ, Conklin, Shupe TF, Beck BD (2007). Evaluating landfill disposal of chromated copper arsenate (CCA) treated wood and potential effects on groundwater: Evidence from Florida. *Chemosphere*, 66(3), 496–504.

Shafiqul Islam M, Kanti Baul P, Haque O (2018). Observation of chloride permeability between normal aggregates concrete and recycled aggregates concrete containing fly ash and clay. *Challenge Journal of Concrete Research Letters*, 9 (4), 103–109

Sharkawi AM, El Mofty SEDM, Showaib EA, Abbass SM (2018). Feasible construction applications for different sizes of recycled construction demolition wastes. *Alexandria Engineering Journal*, 57(4), 3351–3366.

Smith ED, Bishop BS (2005). Benefits to groundwater quality by diverting construction and demolition wastes from landfills. *International Journal of Environmental Technology and Management*, 5(2/3), 230.

Soto-Paz J, Arroyo O, Torres Guevara LE, Parra-Orobio BA, Casallas-Ojeda M (2023). The circular economy in the construction and demolition waste management: A comparative analysis in emerging and developed countries. *Journal of Building Engineering*, 78, 107724.

Tabsh SW, Abdelfatah AS (2009). Influence of recycled concrete aggregates on strength properties of concrete. *Construction and Building Materials*, 23(2), 1163–1167.

Tam VWY, Soomro M, Evangelista ACJ (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials*, 172, 272–292.

Tayeh B A, Al Saffar DM, Alyousef R (2020). The Utilization of Recycled Aggregate in High Performance Concrete: A Review. *Journal of Materials Research and Technology*, 9, 8469-8481.

homas C, Setién J, Polanco JA, Cimentada AI, Medina C (2018). Influence of curing conditions on recycled aggregate concrete. *Construction and Building Materials*, 172, 618–625.

Thomas C, Setién J, Polanco, Alaejos P, Sánchez de Juan M (2013). Durability of recycled aggregate concrete. *Construction and Building Materials*, 40, 1054–1065.

Ulubeyli S, Kazaz A, Arslan V (2017). Construction and demolition waste recycling plants revisited: Management issues. *Procedia Engineering*, 172, 1190–1197.

Wang L, Wang J, Qian X, Chen P, Xu Y, Guo J (2017). An environmentally friendly method to improve the quality of recycled concrete aggregates. *Construction and Building Materials*, 144, 432–441.

Wang Y, Sikora S, Kim H, Dubey B, Townsend T (2012). Mobilization of iron and arsenic from soil by construction and demolition debris landfill leachate. *Waste Management*, 32(5), 925–932.

Wang B, Yan L, Fu Q, Kasal B (2021). A comprehensive review on recycled aggregate and recycled aggregate concrete. *Resources, Conversation and Recycling*, 171, 105565.

Wang D, Lu C, Zhu Z, Zhang Z, Liu S, Ji Y, Xing Z (2023). Mechanical performance of recycled aggregate concrete in green civil engineering: Review. *Case Studies in Concrete Materials*, 19, e02384.

Weber WJ, Jang YC, Townsend TG, Laux S (2002). Leachate from Land Disposed Residential Construction Waste. *Journal of Environmental Engineering*, 128(3), 237–245.

Xiao J (2018). Recycled Aggregate Concrete Structures. Springer Berlin Heidelberg.

Xuan D, Zhan B, Poon CS (2017). Durability of recycled aggregate concrete prepared with carbonated recycled concrete aggregates. *Cement and Concrete Composites*, 84, 214–221.

Zhang J, Kim H, Dubey B, Townsend T (2017). Arsenic leaching and speciation in C&D debris landfills and the relationship with gypsum drywall content. *Waste Management*, 59, 324–329.