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Engineering Properties of Substrate used in Constructed Wetlands Treating low Strength Sewage under Tropical Conditions

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ABSTRACT

Substrates play a major role to filter, adsorb, sediment, flocculate, precipitate, and exchange ions. In CW (Constructed wetland), selecting substrate or bed materials is not difficult, as locally accessible, cost-effective, and environment-friendly materials can be used based on size, hydraulic conductivity, texture, porosity, etc. CW substrates undergo a multitude of purification processes, including physical filtration and sedimentation, sorption, ion exchange and microbial degradation, precipitation, and bio-immobilization in the substrate, in addition to uptake and metabolism by macrophytes. With constructed wetlands, treatment facilities with well-defined substrates, vegetation species, and flow patterns can be built with greater control than with natural systems. This report details investigations of some of the locally available substrates that all fit the requirements. Based on analysis of parameters which are pH, water absorption capacity, hydraulic conductivity, porosity, surface area, bulk density, particle size distribution, D10 particle diameter, D60 uniformity coefficient, permeability and specific gravity, a comparison of four materials is presented in this paper. The study found that the construction waste materials evaluated showed satisfactory physical properties for use as filler media in constructed wetlands for wastewater treatment.

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INTRODUCTION

Wetlands serve as a place of transition. On the coast, near bodies of freshwater lakes and rivers, or as mudslides that cover large areas of the countryside, they can be found between dry land and open water. They can also be found along the coast, sandwiched in between the dry land and the open water. As a transition zone between land and water ecosystems, wetland ecosystems can be viewed as an ecological bridge. Due to the natural process of plant succession and sinking water tables, the vast majority of wetland areas will either become dry land or submerged due to rising water tables as a result of relative sea-level rise or climatic change because wetland communities are often part of a larger community continuum, defining their boundaries can be difficult (Mitsch & Gosselink, 2015).

Construction wetlands (CW) are used to treat industrial wastewater from paper pulp mills and seafood processing, as well as residential, agricultural, Coal drainage, petroleum reactor effluent, compost/ landfill (organic manure) effluent, leachates, fish pond effluent, and other sources. In the right hands, CW can be an affordable and effective treatment option (Davis L,1995). A man-made wetland can also be used as recreation purposes in urban areas. Plants, weeds, substrates,

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microorganisms, water, and various filters (sand, gravel, dirt, etc.) are all components of the constructed wetland system (Vishwakarma & Dharmendra, 2022). The constructed wetland treatment is a viable solution that does not potentially harm downstream water bodies. The two types of constructed wetland are free water surface flow constructed wetland (FWSCW) and sub-surface flow constructed wetland. Vertical (VF) CW flow, horizontal (HF) CW flow, and a hybrid type CW flow are all types of subsurface flow (Vymazal & Kröpfelová, 2008). Wetlands have been employed since generations to treat wastewater. However, in many cases, the wetland was used as a disposal site because it was fairly close to river or other canal, rather than for treatment (Reddy & Smith, 1987). Many wetlands around the world have been destroyed as a result of uncontrolled wastewater disposal. Even in the 1970s and 1980s, attempts were made, mostly in the United States (Kadlec et al., 1979) to utilise natural wetland habitats for wastewater treatment under controlled conditions (Ewel et al., 1982). Using natural wetlands as a test bed revealed that not only was system upkeep difficult, but treatment efficacy was also unpredictable (Olson, 1993). Since 1960s, man-made wetlands (CWs) have been developed as a technique of eliminating contaminants from wastewater by replacing natural wetlands.

In 1968, Hungary established a free water surface constructed wetland to treat different types of wastewaters, such as domestic, municipal, and industrial waste (Kadlec & Wallace, 2009). Engineers in the United Kingdom constructed an underground flow system using gravel as the media for the bed, which is sloped at the bottom to provide a gradient for the bed's water flow. Long-term stability is maintained by the constructed wetland. Plant uptake reduces only a small percentage of metals and metalloids (Paulo et al., 2013). Constructed wetlands are capable of treating various types of wastewaters ranging from agriculture (Saeed &Sun, 2012) and dairy (Yazdani & Golestani, 2019) to textile (Mbuligwe, 2005), pulp and paper industries (Knight et al., 2000). Agricultural wastewater contains persistent organic pollutants and fertiliser that remain in the food chain, causing severe public health problems; however, wetland plant species can safely remove these contaminants/pollutants from the food chain (Ngweme et al., 2021).

Engineered wetland systems designed to eliminate contaminants from wastewater are engineered systems that replicate natural wetland processes in a more regulated manner. With constructed wetlands, treatment facilities with well-defined substrates, vegetation species, and flow patterns can be built with greater control than with natural systems. In addition, it is essential to note that constructed wetlands have several advantages over natural wetlands, including selecting site location, dimensions flexibility, and, most importantly, control over hydraulic channels and residence time. Constructed wetlands cannot operate effectively without plants, but their role in pollution abatement is indirect, including the insulation of subsurface flow systems, the requirement of oxygen to otherwise anoxic substrates, the requirement of surface for attached microbes, the excretion of antimicrobial compounds from the roots, and the reduction in wind speed that enables better sedimentation of suspended solid in surface flow CWs. If the organic matter is harvested, the primary function is lowered to nutrient absorption.

The Working principle and components of Constructed Wetland are as such: Constructed Wetlands are engineered systems that are constructed and designed to utilise natural processes that to utilise natural processes that purify and improve the quality of water (Ingrao et al., 2020). Constructed wetlands are artificial wetland systems in which treatment occurs by combined efforts of plants and naturally occurring chemical, biological, and physical processes for the removal of pollutants (Sudarsan et al., 2015). Nitrification, denitrification, absorption, adsorption, and physico-chemical processes, such as Phosphate fixation by iron and aluminium in the soil filter, are the three primary mechanisms responsible for the operation of constructed wetlands. Whereas in the removal of effluents from industrial and mine drainage processes such as oxidation of metals, co-precipitation of some elements, Microbial sulfate reduction and ion-exchanging capacity takes place (Stottmeister et al., 2003). The preliminary treatment of wastewater removes floating contaminants, grit particles, and oil. The outflow from the preliminary treatment is linked to the sedimentation tank, where sediments settle, and biochemical oxygen demand (BOD) is lowered. The outlet of preliminary treatment is linked to the sedimentation tank, where solids settle, and biochemical oxygen demand (BOD) is reduced. In addition to playing a significant role in the removal of pollutants and nutrients from wastewater, the media and macrophytes also play an important role. The rhizosphere of macrophytes enhances the processes (Shukla et al., 2021).

The study aims on analysis of parameters which are pH, water absorption capacity, hydraulic conductivity, porosity, surface area, bulk density, particle size distribution, D_{10} particle diameter, D_{60} uniformity coefficient, permeability and specific gravity and a comparison of four materials is presented in this paper. The study found that the construction waste materials evaluated showed satisfactory physical properties for use as filler media in constructed wetlands for wastewater treatment.

MATERIAL & METHODS

Substrates play a major role to filter, adsorb, sediment, flocculate, precipitate, and exchange ions. The aggregates are thoroughly cleaned, dried, and sieved into their individual "fractions" or size ranges.

Equation 1 is applied to calculate porosity (P):

$$P = 100\,((1 - (D/D_r) \qquad 1$$

where,
P: porosity (%)
D: compacted density of dry aggregate
D_r: relative density of mixed aggregate (gr/cm^3)
D_r is obtained from Equation 2:

$$D_{rn} = 100/\,(\sum P_{wi}/D_{ri}) \qquad 2$$

where,
D_{rn}: relative density of the n aggregate mixture.
P_{wi}: percentages of aggregate from fraction i
D_{ri}: relative aggregate density of fraction i (Hardiman, 2004).

In CW, selecting substrate or bed materials is not difficult, as locally accessible, cost-effective, and environment-friendly materials can be used based on size, hydraulic conductivity, texture, porosity, etc. CW substrates undergo a multitude of purification processes, including physical filtration and sedimentation, sorption, ion exchange and microbial degradation, precipitation, and bio-immobilization in the substrate, in addition to uptake and metabolism by macrophytes. Physicochemical properties of the substrate, such as particle size distributions, effective particle sizes, porosity, water absorption capacity, interstitial pore spaces, irregularity degrees and the permeability coefficient, coefficient of uniformity, and specific gravity, have such a significant impact on the CW treatment system. There are chemical properties also that influence nutrient removal efficiency in CW systems like pH, Electrical conductivity, and organic matter. The most widely used substrate are soil, sand, and gravel with different particle size (Kataki et al., 2021).

There occurs a serious problem of substrate clogging in Constructed Wetland which is of major concern. It is caused by inadequacies in some of the material's properties, such as smaller particle sizes, poor hydraulic conductivity, low permeability, and the accumulation of dissolved and suspended solids on their surface, which reduces the system's overall performance and shortens its lifespan. This issue can be solved by: (a) increasing the porosity of the substrates; (b) anti-sized setup by using multi-layer substrates with coarse grains on the top surface layer and finer grains in the intermediate or bottom layers; (c) permeable medium such as microfibers installed along the inlet and outlet area of the CWs; and (d) avoiding the utilization of substrates that can react with pollutants (Yang et al., 2018).

This study investigates a variety of substrates that meet the aforementioned criteria. Based on measurements of pH, water absorption capacity, hydraulic conductivity, porosity, bulk density, specific surface area and particle size distribution, D_{10} particle diameter, D_{60}, uniformity coefficient, permeability and specific gravity, a comparison of four materials is presented in the study.

Hamirpur district is centered in Himachal Pradesh (India). Hamirpur is located between the coordinates 31° 21 00 and 31° 53 00 North and 76° 16 00 and 77° 45 00 East (Fig. 1). 82% of the annual precipitation begins to fall between July and September (monsoon).

Geomorphologically, the area is predominantly hilly and undulating, with an altitude range of 600 to 900 meters above mean sea level. The northeastern and southeasterly regions of the district form the Sutlej and Beas drainage networks, subsequently. There are dendritic and sub-dendritic drainage trends with medium to coarse drainage density. According to the Central Ground Water Board of India's (2019) survey, Hamirpur is a secure district because its groundwater resources are not sufficiently developed, leaving a substantial amount of potential for future development (Kumari et al., 2022).

This study investigated the physicochemical properties of four substrate materials: soil, fine and coarse aggregates, brick waste, and demolished construction waste. These substrate materials were sourced from regions close to the National Institute of Technology campus in Hamirpur, Himachal Pradesh.

The formation of stone aggregates is a broad category resulting from soil processes. It consists of fine, medium, and coarse grains (Sveistrup et al., 2008). Aggregate which passes through 4.75-mm IS Sieve are fine aggregates which consists of Natural Sand, Crushed Stone sand and Crushed gravel sand. Coarse aggregates are the aggregates which retains on 4.75mm IS sieve. All in aggregates consists of fine and coarse aggregates (IS: 383- 1970).

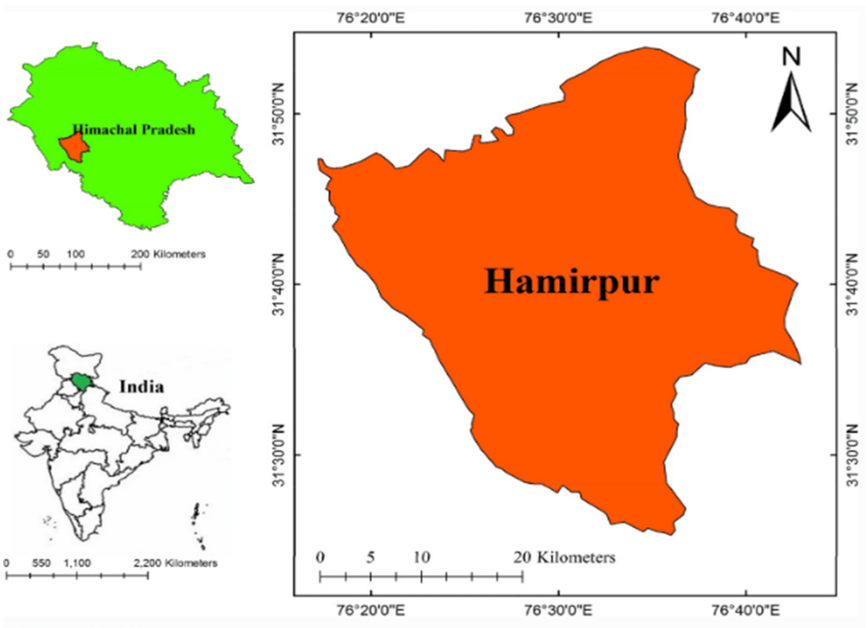

Fig. 1. map of Hamirpur district (Kumari et al., 2022)

The term “construction waste” refers to leftover materials, silt, abandoned bricks, and other residual waste generated during the building works, establishing, destruction, and fixing of various buildings and pipelines. Utilizing construction waste is a promising strategy for lowering its disposal expenses. This phrase refers to the concrete produced by mixing used concrete blocks with water and cement. Recycled concrete can entirely or partially substitute mineral admixtures such as stone and sand. Recycled aggregates are currently used in all nations for a variety of civil engineering applications, including road pavement materials, subbasements, soil stabilization, sub-ground improvement, and the production of numerous types of concrete (Wang et al., 2020).

Soil is an essential component of the earth’s ecosystem. The soil used is locally available soil. Numerous studies have been conducted using soil as the natural substrate and demonstrated that soil exhibits excellent phosphorus sorption capacity and adsorb heavy metals and help in their removal. Soil particles usually get broken down by weathering and erosion and get washed away by rain and storm. Soil will form the base for the growth of vegetation and will help the roots for supplying oxygen. Different soil gives different efficiencies accordingly (Wang et al., 2020).

These are typical types of construction waste. Brick wastes are polyporous and abundant in calcium (Ca), iron (Fe) and aluminum (Al), making them promising and favorable as substrates. Broken bricks facilitate microorganisms and help in plant growth in CWs (Shi et al., 2017).

Analysis for the physical properties of the substrate material were performed. Different tests performed on the material were pH, sieve analysis, water absorption test, Specific Gravity, Bulk Specific Gravity, Dry density, Porosity, Coefficient of Uniformity (C_u), Coefficient of Curvature (C_c) and Void Ratio.

The pH of the material was tested using a pH meter (Model no. LMPH-10, Labman).

Sieve Analysis is performed for soil using 4.75mm,2.36mm, 1.12mm, 600µ, 425µ, 300µ,150µ, 75µ and pan. For aggregates 20mm, 12.5mm, 10mm and 4.75mm sieves were used. Sieves of 20mm, 12.5mm and 10mm were used for brick and for Demolished Concrete Waste. The tests were conducted using the standard procedures (Kirthika & Singh, 2020) (Drizo et al., 1999).

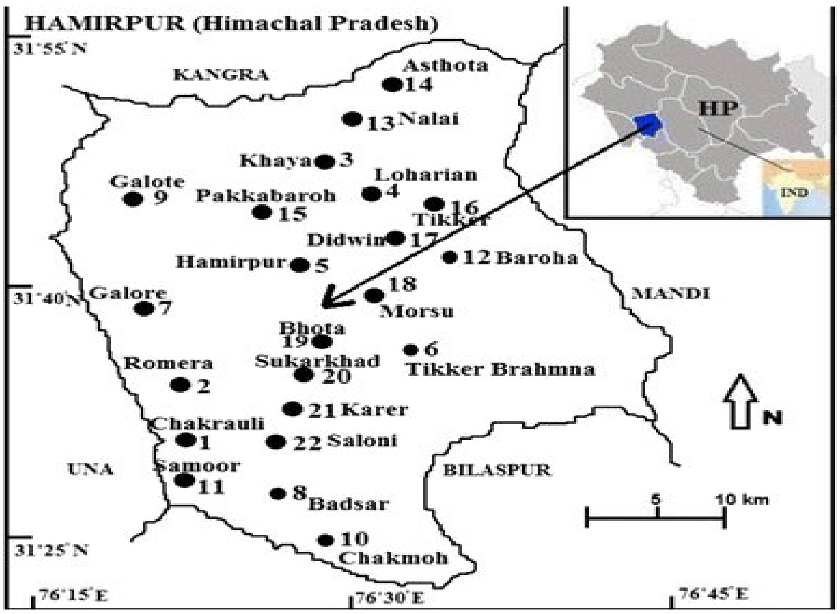

Fig. 2. location of the study area (Singh et al., 2016)

a)

b)

c)

Fig. 3. Substrates used for analysis.
(a) Demolished Concrete waste, (b) brick waste, (c) stone aggregates.

It was necessary to conduct a test to determine the capacity of Water Absorption of stone aggregates, recycled concrete aggregates (RCA), and brick aggregates. The method for determining the water absorption capacity of a material involves measuring the weight of a sample after it has been immersed in water for 24 hours and again after it has been dried in an oven. Absorption capacity is the difference in weight, expressed as a percentage of the dry sample weight (Ibrahim et al., 2013).

Specific gravity of the aggregates and the demolished construction waste i.e., the brick and the concrete waste was determined using the Pycnometer method.

The loose bulk density was determined using a cylindrical mould with a 1000 cm^3 volume and a 10 cm inner diameter.

Estimation of bulk density and specific gravity were found out to compute porosity (Patyal et al., 2022). The porosity of substrates should not be lower otherwise can cause clogging in the system. The porosity of the substrate closely affects the permeability of the system which further affects the clogging in the system (Wang et al., 2021).

$$Porosity\,\% = 1 - \frac{substrate\ bulk\ density}{substrate\ specific\ gravity} \times 100\,\% \qquad 3$$

$$K_{60} = \frac{D_{60}}{D_{10}} \qquad 4$$

where D_{10} and D_{60} (mm) are the diameters of particle sizes of a substrate material at which 10% and 60% of the particles does not retains and passes through the sieves, respectively, and K_{60} is the uniformity coefficient and K_{60} is the uniformity coefficient (Cui et al., 2008).

The permeability of the samples was determined using the falling head permeability test. Pervious concrete specimens were cast in a 10cm diameter, 15 cm long pipe mold for all the 14 mixes prepared. The test was performed using Permeability testing apparatus using several water heights, which represented values that a pavement may experience in practice. The average coefficient of permeability (k) was determined using Equation:

$$k = 2.303\,\frac{aL}{(At)}\ log\frac{h_1}{h_2} \qquad 5$$

where,
k= coefficient of permeability, a = cross-sectional area of the standpipe, L = length of sample, A = cross-sectional area of specimen, t = time for water to drop from h_1 to h_2,
h_1 = initial water level, h_2 = final water level (Singh et al., 2016).

RESULTS AND DISCUSSION

The physical and chemical properties of the materials were determined in accordance with the IS Codes standard procedure.

The measured values of these parameters are given below in Table1.

The Material whose characteristics found were Aggregates, Bricks, Demolished Construction Waste and Soil. Sieve analysis was done. For aggregates 20mm, 12.5mm,10mm and 4.75mm sieves were used. For bricks 20mm, 12.5mm and 10mm sieve were used. For Demolished Construction Waste 20mm, 12.5mm and 10mm were sieved and for soil 4.75mm, 2.36mm, 1.12mm, 600µ, 425µ, 300µ, 150µ, 75µ and Pan were used. Water Absorption Ratio for aggregates - 20mm= 0.8048 % ,12.5mm= 0.15 %, 10mm= 1.16 % and Fine aggregates = 1.9038%. Bulk Specific Gravity and Apparent specific gravity were found out using the specific methods mentioned in IS Codes. Bulk Specific Gravity of aggregates 12.5mm was found out to be 1.7 for 10mm was 2.74, for bricks was 1.743, for Demolished construction waste (Concrete) was 1.525 and for soil 2.30. Apparent Specific Gravity for aggregates 12.5mm was found to be 2.73, for 10mm was 2.050, for bricks 2.38, for demolished concrete waste was 2.329 and for soil was 2.46. Other properties were also found out i.e. dry density, porosity, void ratio, coefficient of uniformity C_u, C_c, D_{10} and D_{60}. For aggregates dry density (γ_d) = 1677.2 kg/m^3, e = 0.624 and porosity = 0.324. For bricks Porosity= 0.234 and void ratio (e)= 0.305. For Demolished Concrete Waste Porosity= 0.34-0.35 and e= 0.515. For soil coefficient of uniformity (C_u) = 13.86, coefficient of Curvature (C_c)= 0.344, (D_{10}) = 78.99 µm, D_{30} = 179.85µm and D_{60} = 1094.7 µm, Void ratio, e = 0.431 and Porosity 0.301.

Table 1. the test results of the substrate characteristics

MATERIAL	Sieve used	Water Absorption Ratio	Bulk Specific Gravity	Apparent specific gravity	Other findings
AGGREGATES	20mm 12.5mm 10mm 4.75mm	20mm= 0.8048 % 12.5mm= 0.15% 10mm= 1.16% Fine aggregates = 1.9038%	12.5mm = 1.7 10mm = 2.740	12.5mm= 2.73 10mm= 2.050	γ_d = 1677.2 kg/m^3 e = 0.624 porosity = 0.324
BRICKS	20mm 12.5mm 10mm	20mm = 17.1% 12.5mm= 15.36% 10mm = 13.43%	1.743	2.38	Porosity= 0.234 e= 0.305
DEMOLISHED CONSTRUCTION WASTE	20mm 12.5mm 10mm	20mm= 22.63% 12.5mm = 17.43% 10mm = 15.2	1.525	2.329	Porosity= 0.34-0.35 e= 0.515
SOIL	4.75mm 2.36mm 1.12mm 600μ 425μ 300μ 150μ 75μ Pan	16.97%	2.30	2.46	C_u = 13.86 C_c = 0.344 D_{10}= 78.99 μm D_{30}= 179.85μm D_{60}= 1094.7μm Void ratio, e =0.431 Porosity = 0.301

CONCLUSIONS

In recent findings to promote a recycling program, there has been an increase in the reuse of discarded materials for wastewater treatment. The purpose of this research was to determine the chemical and physical attributes of construction waste material to be used as filler media in CWs for the removal of pollutants from wastewater. The substrate media selected were aggregates, demolished bricks, demolished concrete waste and soil which is generally disposed of. The current research led to the following conclusions: Physical and chemical parameters such as pH, sieve analysis, water absorption test, Specific Gravity, Bulk Specific Gravity, Dry density, Porosity, Coefficient of Uniformity (C_u), Coefficient of Curvature (C_c), and Void Ratio were used to evaluate the waste materials. All the materials showed adequate physical properties for successful hydraulic operation in CWs. Based on the findings of this study, it can be concluded that all the investigated materials - aggregates, bricks, demolished construction waste, and soil have suitable physical properties for use in constructed wetlands as pollutant removal media. However, the specific characteristics of each material, such as their water absorption ratio, bulk and apparent specific gravity, and porosity, differ and should be taken into consideration when selecting the appropriate material for a given application.

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The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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