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A Comparative Evaluation of Embodied Environmental Impacts of Channel Stabilisation Using Concrete Lining and Alternative Pozzolanic Materials

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Abstract

Channel stabilisation with the lining of bed/ banks using cement-concrete (with/ without steel reinforcement as per the size, depth, and capacity), geomembrane, polymers, canvas, ramped earth, vegetation, gravel/ stone pitching, and brick blast is a common practice worldwide to save the adjacent flood plain areas from bank overflowing, seepage, water logging/ salinity, loss of water in irrigation channels, maintaining required water levels and strengthening of channels to be used as transportation means. A trapezoidal channel of cross-section 165 m^2 and a lined perimeter of 42m was proposed to accommodate a super flood of 360 m^3/sec discharge for a catchment area of 1446 km^2 and 118 km length, using a projected heavy flood event of 6 cm precipitation in 8 hours for Swale River to ascertain the material calculation and its environmental impact. This concrete lining would likely produce an equivalent global warming potential/ embodied carbon dioxide (CO_2) of 284 million kgCO_2eq (kilogram CO_2 equivalent) with the projected use of around 271 million kg of cement concrete and 78 million kg of steel. The enormous amount of embodied CO_2 emissions from this projected lining project suggested using natural means of flood/ channel protection if feasible, or alternative supplementary cementitious materials with fibres should be used to minimise the environmental impacts.

Keywords: Hydrology, materials science, channel stabilisation with lining, cement concrete, embodied CO_2, environmental impacts.

Introduction

The natural methods of floodplain restoration are short-lived, limited and less efficient, especially for the extensive stretches of more significant streams. This necessitates the incorporation of structural methods of flood protection in the form of dams, reservoirs, barrages, channels, the concrete lining of rivers and the erection of artificial means/ hydraulic structures, which are considered robust, strong, efficient and resilient but likely to cause environmental/ ecological disorder due to use of cement as a basic material (Nadir & Ahmed, 2022; Nadir et al., 2024; (Nadir, 2024a; 2024b;)). Cement is the leading cause of the carbon footprint of concrete in the construction industry. As professionals in the field, the audience plays a crucial role in finding and implementing sustainable solutions to this issue. Cement is classified as third in the Green House Gas (GHG) emissions after the iron and steel industries, but its large-scale manufacturing/ utilisation of around 4.4 billion tons annually makes it the most CO_2 embodied material in the world. Cement emits 10% of GHG and 30% of global energy consumers (Purnell, 2013; UNEP, 2020; Lupien, 2020; Obinna, 2023). The conversion of limestone $CaCO_3$ into slaked lime CaO after burning at 1450oC is the most energy-intensive and CO_2 emitting process of cement manufacturing, accounting for around 80% of GHG emissions of cement concrete (0.8-0.9 tons of CO_2 per ton of cement manufacturing). Concrete main ingredients are binder (cement responsible for up to 80% of GHG emissions), fine/ coarse aggregate (responsible for up to 5% GHG emissions), admixtures (responsible for up to 2% GHG emissions) and water (zero emissions) (Brander & Davis, 2012; Gagg, 2014; Grand view research, 2020; Nadir & Ahmed, 2021a; Garside, 2022a; Garside, 2022b; MPA, 2007; Nadir et al., 2022b). The construction industry must adopt low-CO_2 embodied construction materials while planning any infrastructure, especially the water channels and proper hydraulic designs, to shoulder the responsibility of reducing carbon footprints. The total discontinuation of cement concrete is not considered an immediate solution. It would likely continue in construction like using fossil fuels for at least a considerable future time, necessitating formulation of greener/

sustainable eco-friendly materials by controlling/ reducing the use of clinker (calcination of lime), reduced cement use, use of alternative pozzolans, use of alternative materials for steel, aluminium and plastic. Therefore, deliberate hydrological/ statistical studies and selecting sustainable construction materials are imperative for the catchment-level management of water resources. Some examples of using cement concrete and supplementary cementitious materials (SCMs) in infrastructure construction/ hydro modifications are illustrated in Figures 1 and 2.

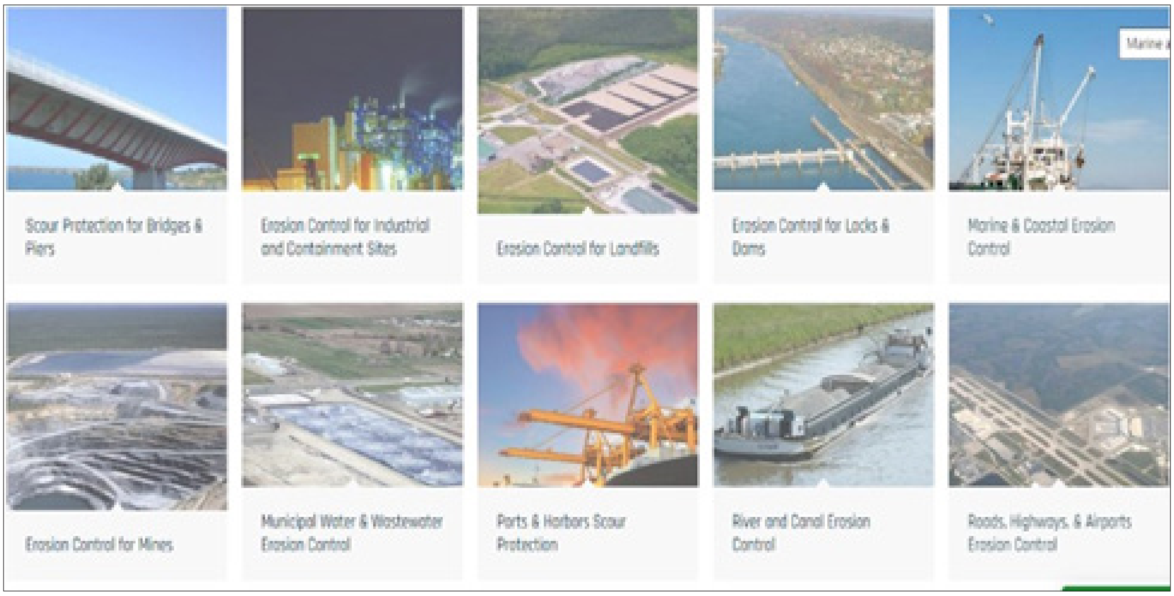


Figure 1: Hydromodifications, Channele/ Stabilisation (Synthetex, 2023)


www.cemex.co.uk, 2023

Geotechnical Engineering, (2023)

www.cemex.co.uk, 2023

www.wikimedia.org, 2024

ABM Landscaping, (2023)

Figure 2: Uses of Cement Concrete and FRC SCMs in Greener Infrastructure Construction and Embankment Stabilisation

Hydrological Studies and Flood Forecasting/ Prevention

Water channels supply drinking water, food, and transportation means for humankind (Shirleyana & Anindya, 2012), but unplanned mushroom growth/ urbanisation along the water channels impact the ecology, hydrology and environment (World Wildlife Fund (WWF), 2012). The construction of hydraulic structures for flood protection, channel stabilisation and taming the natural resources using artificial materials like cement concrete/ steel and heavy hydro-modifications in geography, natural profile/ alignment result in disturbed flow and cue conflicts among the societies (Nadir & Ash, 2022). Historical flooding and its damaging effects on human lives/ property are a few examples of the anthropogenic activities in the floodplains of major rivers and their after-effects of the modifications like the Yangtze River's worst floods and devastation caused by Yellow River in China, Mississippi River in the USA, Indus in Pakistan, Ganges, Jumna and Brahma Putra in India and Bangladesh, Elbe flooding in 2002 in central Europe, the UK flooding in 2007 mainly arising from climatic changes and urbanisation/ modifications along natural rivers flood plains (Prevention Web, 2008; Flood site, 2009; Schleifstein, 2011; Shandana, 2012; Kumar, 2017; National Mississippi River Museum (NMRM), 2018; WIKI2, 2019; Kumar, 2020; Nadir & Ahmed, 2022; US Army Corps of Engineers (USACE), 2024). All these damaging catastrophic events necessitate the incorporation of preventive/ corrective measures to avoid the re-occurrence of flooding events and damages to lives/ property and channels themselves by coordinated studies of hydrology, geography, geology, material sciences, environmental impacts and careful designing/ selection of greener infrastructure construction materials for all types of hydro modifications/ channel stabilisation.

Hydrological studies, statistical modelling and flood frequency analysis are paramount activities before planning any construction along the water streams (Stewart et al., 1999; Helsel & Hirsch, 2010; Saleh, 2011; Renard et al., 2013; Benameur et al.,2017). However, the effectiveness of such hydrological studies largely depends on the selection of statistical techniques/ software and the availability of data for forecasting rainfall/ discharge in a river using different statistical formulas and software. Then, the estimated 10-200 year return period for storm/ discharge events, lag time, hydrograph analysis, catchment efficiency, exceedance probability, probability distribution functions and the expected discharge are calculated to design the suitable channel cross-section, hydraulic structures and channel lining methods (Rowinski et al., 2002; Millington et al., 2011; Renard et al . ,2013; Singo et al., 2013; Bezak et al., 2014; Oke and Aiyelokun, 2015; Saghafian et al.,2014; Deng et al., 2016; Kamal et al.,2016; Rulfova et al., 2016; Mathwave Easy Fit 5.6 Pro, 2019; Liu et al., 2022). These methods use estimation parameters based on the length of the given data set (less than 50 entries or more than 50 entries) (Rowinski et al., 2002; Cunnane, 2010; Nadir & Ahmed, 2022). It is difficult to assess a precise flood event trend; however, a predicted storm event based on the historical flow pattern could demonstrate ideal conditions for flood/ storm forecasting. A unit hydrograph analysis is helpful in the assessment of the effective runoff in a catchment by a storm event for essential flood plain mapping/ zoning, estimation of precipitation/ discharge in a river basin, catchment parameters and rain/ flood frequency duration curves (Jena & Nath, 2019; Adeyi et al., 2020; Iresh et al., 2024; Iresh et al., 2024; Shashika et al., 2024).

Channel Lining Designing Parameters

The channels are lined to protect the water losses due to infiltration in the soil during water transportation from head to tail in different reaches. The unlined canal raises the water table in the surrounding areas, causing saturated soil, water logging and salinity, and loss of precious water (especially if a channel is used for irrigation). The first and foremost design parameter is the impact of lining on the environment/ ecology/ natural habitat of the stream. The economic consideration comes next to deciding whether to construct a lined channel or let it be in the natural strata. The velocity of water, erosion control, structure/ alignment of channel (straight/ meandering), water inflow/ capacity, resistance to storm flow, type/ nature of soil strata of the channel catchment, area of the channel, shape of the cross-section and use/ type of materials are a few important considerations before finalising the decision of lining the channels and use of materials/ techniques. Due to ecological considerations, preserving channels in their natural geographical profile is the best strategy. However, the areas causing frequent overflowing of the banks/ flooding, erosion, sediment/ gravel deposition, and safety to surrounding assets/ properties are considered for channel linning/ stabilisation, even compromising the ecological implications. The necessity of incorporating engineering solutions to safeguard the channel embankments, structures (bridges, culverts, weirs, notches) and human beings/ assets is prioritised with minimal environmental impacts. Generally, the lining could be stone/ brick pitching, wooden logs, gravel revetment or vegetation for a low discharge channel. Nevertheless, plain cement concrete with/ without fibres, canvas, meshes, polypropylene tubes/and reinforced earth/ panels are considered eco-friendly solutions for a high discharge channel. However, for very high discharge or in the case of poor bank strata, the use of reinforced cement concrete is considered the long-lasting lining solution (Gnilsen, 1987; Leika et al., 2000; UK Centre for Ecology & Hydrology, 2022; Tahir et al., 2011; FSU, 2012; UK Centre for Ecology & Hydrology, 2013; Memon et al., 2013; NRFA, 2015; Bakhshi & York, 2016; Open Channels, 2016; Ditches and Channels, 2002; Section 44, 2016; The Constructor, 2018; CCLD, 2019; Engineering Toolbox, 2019; Kumar, 2020; United States Department of Agriculture (USDA), 2020; GOV.UK, 2021; Waqas-Chaudhry, 2021; FEG, 2022; Scribd, 2015; Kim & Lee, 2021; United States Department of Agriculture, 2022; UK Centre for Ecology & Hydrology, 2022; Synthetex, 2023).

Methodology and Study Site

The empirical correlation between stream discharge and stage gauge reading is then calculated using the empirical relationship for respective daily stage gauge height; a total volume of direct runoff per hour VDRH is calculated from the total discharge (Doston, 2020; Scribd, 2015). The hydrograph analysis is helpful in the calculation of the intensity of a storm in a specific catchment in a unit of time, which can then be used to assess the multiple storm events' intensities, their lag timing in the conversion of the storm into a discharge from the runoff basing on the catchment efficiency, infiltration, geographical profile and geology taking into consideration the manning N relationships/ strata material values, rational method correlation and lag time formulas (US Geological Survey (USGS), 2016; Engineering Toolbox, 2019; Chegg, 2023). The channel cross-section can be triangular for low discharge capacity or trapezoidal/ rectangular for higher discharge capacities. The trapezoidal cross-section is preferred for its better stability with a 2:1 horizontal to vertical slope in the form of 10-15 m panels with a proper jointing system. The preferable thickness of lining for plain concrete is a minimum of 10-20cm for PCC/ RCC and 20-50cm for bricks/ stone lining (IS: 3873- 19192, 1993; Thomason, 2019; Highway Design Manual, 2020).

Swale River is the northernmost tributary of River Ouse in Yorkshire Dale, one of the fastest flowing water streams in the UK, originating from the Birkdale Common, drains West/ South through Birkdale Deck, East/ North through Whites undale Beck It. It flows easterly over the hamlet of Keld, passes through significant settlements like Richmond and Catterick southwards and ultimately joins River Ure at Myton-on-Swale in the Vale of York near Borough bridge, stretching 118 km length, draining a catchment area of 1446 km2, as shown in the layout map in Figure 3 (Wikipedia Contributors, 2024). The river catchment could generate a maximum of 140m^3/sec base flow discharge. However, the flow range of 10-80 m^3/sec is a normal range for the river in a regular storm event. Therefore, the designers must plan the flood prevention infrastructure's capacity/ strength/ placement to cater to a minimum flood event of 150 m^3/ sec (rounded up). However, for design considerations, the forecast of maximum rainfall/ discharge is done on 100-200 years precedence, which comes to be around 360 m^3/sec, 3 times more than the maximum base flow of 150 m^3/sec. (Yorkshire Dales National Park, 2024; Yorkshire Dales Rivers Trust, 2024; Walks in Yorkshire, 2024).

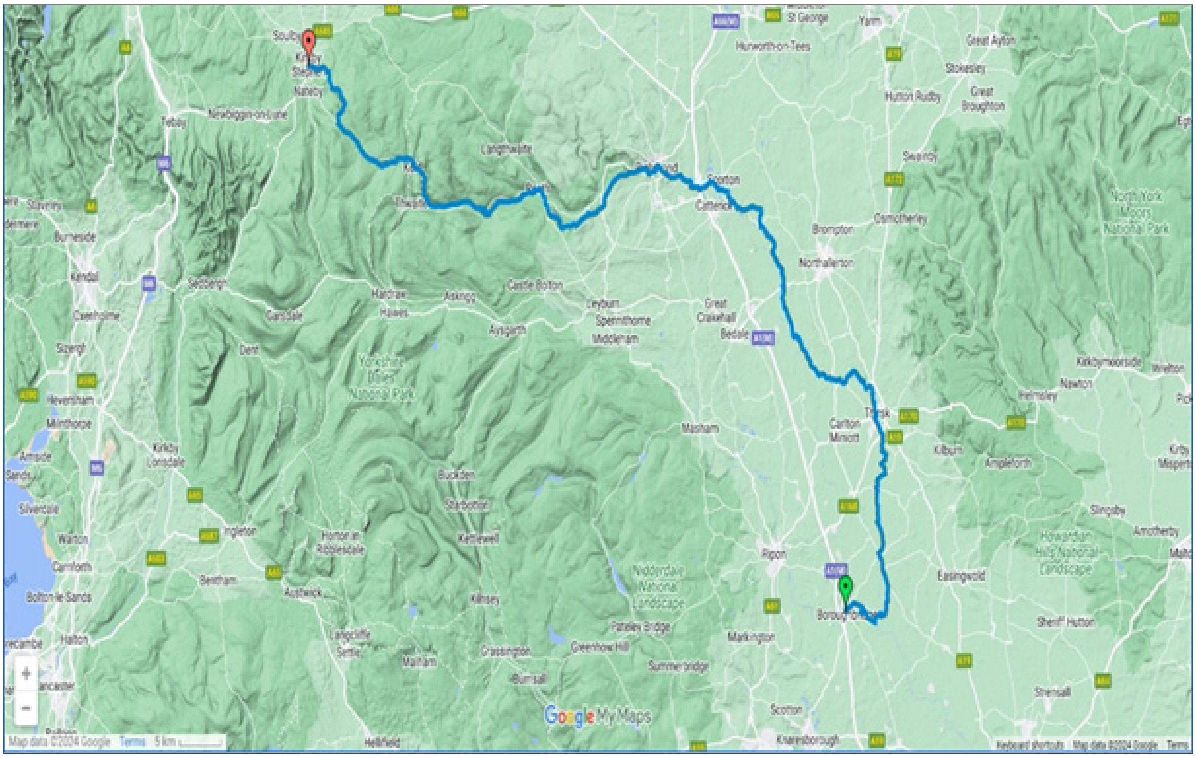


Figure 3: River Swale Map (Swale Way Google Maps, 2024)

Results and Discussion

In another study conducted by the author on hydrology (Nadir, 2024b), A 200-year-return period storm of 2.75 cm/ hr, generating a 200-year discharge event of 360 m3/sec in Swale River, having a catchment area of 1446 km^2 based on a 30% catchment efficiency index. Base flow is subtracted from observed flow to obtain storm flow, and then, the total runoff volume is calculated using Equation 13 or calculating the area under the curve in the hydrograph (Table 1). The equivalent rainfall depth RE has been calculated by dividing VDRH by the catchment area in meters (1446,000,000 m^2) and multiplying it by 100 to get the equivalent rainfall depth in cm. The difference between RT (6 cm) and RE (1.3 cm) indicates 4.7 cm of rainfall loss due to water absorption/ evaporation. The infiltration index of around 30% has been calculated using the expression RE/Rl. The effective rainfall is obtained by subtracting the infiltration index from the hourly rainfall of the storm event. The hydrograph calculations are shown in Table 1. The unit hydrograph obtained by this calculation has been used to calculate the storm hydrograph of any rainfall duration for the same section/ catchment (Table 2) (Nadir, 2024b).

Total Discharge = 14130000 m^3

Equivalent rainfall of total VDRH (in-depth cm) = RE = 14,130,000 /(1446x1000x1000) * 100 = 1.3cm

Total rainfall during the storm event = RT = 0.25+2.75+2.75+0.25 = 6 cm

Total losses of rainfall volume in cm depth = RL = RT (Total Rainfall) – RE (Equivalent Rainfall of total VDRH) = 6 – 1.3 = 4.7 cm

infiltration index (Ø) = RE / RL = 1.3/4.7 = 28% ≈ 30%

Effective rainfall = Total rainfall – Ø (no negative value to be considered)

Total Peak Discharge = 1200 m^3/sec

30% Peak discharge after infiltration @ 30% catchment efficiency = 360 m^3/sec

Generally, in the given catchment area of Swale River in the above data, flood events occurred after the peak rainfall with a 1 to 5-hour lag time and finished in 12 hours to return to the regular base flow. The probability of getting high discharge runoff in lesser lag time is higher in case of more rain in consecutive intervals of time in wintery/ wet conditions, concluding that a prolonged spell of rain has a higher probability of a flash flood event (Nadir, 2024b).

Table 1: Quantities of discharge and precipitation duration for a 200-year predicted hydrograph analysis (Nadir, 2024b).

Rainfall Duration(h)	Total Rainfall (cm/hr)	R_E	Flow Time (h)	Observed Hydrograph m^3/sec	storm Hydrograph m^3/sec	Unit Hydrograph m^3/sec	Runoff Volume m^3
			0	150	0	0	0
0 - 1	0.25	0	1	150	0	0	0
1 - 2	2.75	2.25	2	350	200	50	720000
2 - 3	2.75	2.25	3	800	650	162.5	2340000
3 - 4	0.25	0	4	1200	1050	262.5	3780000
			5	900	750	187.5	2700000
			6	750	600	150	2160000
			7	550	400	100	1440000
			8	350	200	50	720000
			9	225	75	18.75	270000
			10	150	0	0	0
			11	150	0	0	0
Total	6						14130000

Table 2: Embodied CO_2 ($kgCO_2e/kg$) of Cement, aggregate and SCMs (Nadir, 2024b)

Time (h)	Unit Hydrograph (UH.)	P1*UH	P2*UH	P3*UH	P4*UH	Storm Hydrograph (DRH)	Total Hydrograph (TH.)
1	0	0				0	150
2	50	100				100	250
3	163	325	0			325	475
4	262.5	525	150			675	825
5	187.5	375	487.5	0		862.5	1012.5
6	150	300	787.5	75		1162.5	1312.5
7	100	200	562.5	243.75	0	1006.25	1156.25
8	50	100	450	393.75	25	968.75	1118.75
9	18.75	37.5	300	281.25	81.25	700	850
10	0	0	150	225	131.25	506.25	656.25
11	0	0	56.25	150	93.75	300	450
12			0	75	75	150	300
1			0	28.25	50	78.125	228.125
3				0	25	25	175
14				0	9.375	9.375	159.375
15					0	0	150
16					0	0	150

Channel Lining Designing Parameters

After doing all the designing calculations, we could ascertain that a storm of accumulated rainfall of 6cm could generate a total discharge of 1200 m^3/sec in the catchment. With a 30% catchment efficiency/ infiltration index, only 360 m^3/sec (30% of total discharge 1200 m^3/se) would enter the stream in 4-5 hours. A trapezoidal channel (Figure 4) of 15m base width, 40 m top width, 1 m freeboard, 1 m side extensions, 13.4 m side length, 0.2 m thickness, 6 m depth, 2.6 m/sec flow velocity, area of cross-section 165 m^2, wetted area of cross-section 137.5 m^2, wetted perimeter 41m, total lined perimeter 44 m, hydraulic radius 4m, side slope 2:1, and longitudinal slope 0.045, manning n for concrete 0.013, was proposed to accommodate 360 m^3/sec discharge, for a catchment area of 1446 km2, and 118 km length of the Swale River.

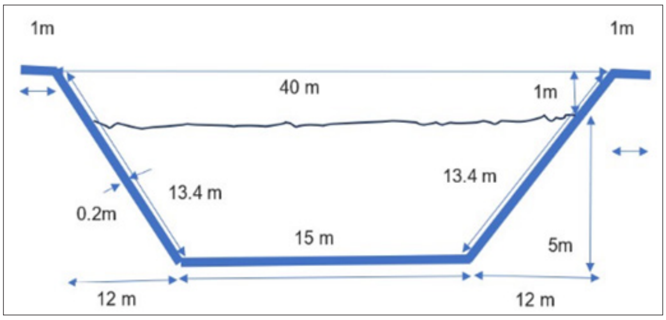


Figure 4: Proposed Channel Cross-Section for Swale River Channelization.

Material Calculations and CO2 Emissions by Concrete Channel Lining

The required strength of concrete was considered 30 MPa at 28 days of cube testing, the mix ratio is 1:2:3, and the reinforcement requirement was taken as 1% of the concrete (Team, 2018). So, the concrete and steel requirements were calculated as follows:

Total concrete required = 42 x 0.2 x 118000 = 991200 m^3
Concrete weight = 991200 x 2400 = 2,378,880,400 kg = 2,378,880 tons
Cement required for 991200 m^3 of concrete in 1:2:3 ratio (@274 kg/ m^3) = 274 x 991200 = 271,588,800 kg = 271.589 tons of cement

Steel reinforcement (@1% = 78 Kg/m3)= 78 x 991200 = 77,313,600 = 77314 tons

The GHG emissions from concrete and steel required lining of Swale River channels of the above-proposed cross-section were calculated using embodied CO_2 data from Table 3 with C25/30 concrete having 0.113 $kgCO_2eq$/ kg and steel having 0.198 $kgCO_2eq$/ kg (Institution of Civil Engineers (ICE), 2011; Obinna, 2023):

CO_2 emission from concrete = 0.113 x 2,378,880,400 = 268,813,485 $kgCO_2eq$ = 5,159,568 tons
Cement required for 991200 m^3 of concrete in 1:2:3 ratio (@274 kg/ m^3) = 274 x 991200 = 271,588,800 kg = 271.589 tons of cement
Cement CO_2 emission = 0.78 x 271,588,800 = 211,839,264 $kgCO_2eq$ = 211839 tons

Steel CO_2 emission = 0.198 x 77,313,600 = 15,308,093 $kgCO_2eq$ = 15308 tons
Total CO_2 emissions from the proposed channel = 268,813,485 + 15,308,093 = 284,121,578 kgCO2eq = 284.12 million $kgCO_2eq$ or 5,159,568 + 15308 = 5,174,876 tons 5.12 million tons CO_2.

This study on the designing/ application of channel lining demonstrates that constructing a 118 km long channel with a 20 cm thick RCC lined channel would likely contribute around 284.12 million $kgCO_2eq$ or 5.12 million tons. Therefore, it is suggested that alternative pozzolanic/cementitious materials and fibres should be used to partially replace cement/ steel in the concrete to overcome this menace of CO_2 emissions from the construction industry, especially on the water line.

Table 3: Embodied CO_2 ($kgCO_2e$/kg) of Cement, aggregate and SCMs (ICE, 2011; Obinna, 2023; Nadir et al., 2024).

Embodied CO_2 $kgCO_2e$/ kg of cement, aggregate and SCMs	
Materials	Embodied CO_2 ($kgCO_2e$/ kg)
Cement Type I	0.78
Sand	0.005
Coarse Aggregate	0.005
Ground Granulated Blast Furnace Slag (GGBS)	0.067
Pulverised Fly ash (PFA)	0.004
Silica fume (SF.)	0.028
Metakaolin (MK)	0.15
Natural Pozzolans (e.g., volcanic ashes, trass)	0.05
Calcined Natural Pozzolans (e.g., calcined clay, LC3)	0.2
Agricultural ashes /rice husk, palm ash (RHA, PA)	0.1
Limestone fines ($CaCO_3$)	0.075
Alkali-activated materials / "Geopolymers."	0.15-0.4
Steel	2.89
RCC 32/37 (110 kg/m3 of steel)	0.2
Aluminium	8.5

Applications of Pozzolanic Supplementary Cementitious Materials (SCMs) in Channel Stabilisation, Hydromodifications and Infrastructure Construction

The study evaluated that channelizing even in a small section of around 118 km long, 42 m wide, and 20 cm thick concrete 1:2:3 lining with 1% steel reinforcement (20 mm c/c 300 mm) resulted in 284.12 million $kgCO_2eq$ or 5.12 million tons. An emission of around 15 million $kgCO_2eq$ by steel, 212 million $kgCO_2eq$ by cement and 57 million $kgCO_2eq$ by fine/ coarse aggregate/ other materials would be contributed by this channelisation project (a total of 279 million $kgCO_2eq$, contributed by 1:2:3 PCC 3000 psi or 21 MPa strength) alone. However, the researchers have been endeavouring to formulate SCMs by partial cement replacement in concrete with pozzolanic materials to reduce the embodied CO_2 emission potential and decrease the construction industry's greenhouse gas emissions. Some of the recommended established/ novel materials have been listed in Table 4 to compare their embodied CO_2 potential to that of cement. All partial replacement pozzolanic materials, except for the metals, demonstrate significantly less embodied CO_2 than cement. Nevertheless, the use of metals (600-800 million tons annually) compared to cement (around 3.5 billion tons annually) in the construction industry is significantly less. Hence, the cumulative effect of cement's greenhouse gas emissions is much more pronounced as the significant CO_2 emitter in the construction industry. Cement is the second largest CO_2 emitter, responsible for 10% of the global emissions after the power production industry (35% CO_2 emissions), even more than the aviation industry (7% CO_2 emissions) (Ahmed & Nadir, 2024).

As shown in Table 4 and Table 5 (Appendix I), if the partial replacement of cement is considered beneficial with pozzolanic SCMs, like using 30-60% ground granulated blast furnace slag (GGBS), then a 27-53% saving in CO_2 emissions and a cost saving of 5-10% can be achieved. Using 10-40% pulverised fly ash (PFA) can reduce CO_2 emissions by 10-39% and economise on the cost by 3-12%. Silica fume (SF) is obtained from the silicon industry and is a costly material; therefore, its 2.5-10% use as SCM can reduce CO_2 emissions by 2-9%, but the cost is likely to increase by 2%. Metakiolin is produced by calcining/ dehydrating Kaolinite (naturally occurring clay) by burning at 650-700 centigrade. It is abundant, like limestone, and can be widely considered a partial replacement for cement. Still, its calcination process makes it a higher CO_2 embodied material with increased manufacturing cost. Still, its 5-20% use can save on emissions by up to 16% with a cost benefit of up to 3%. Rice husk ash (RHA) and palm ash (PA) are agricultural waste ashes whose 2.5% to 10% use as a novel material is under consideration and can result in reduced CO_2 emissions by up to 9% and a cost-benefit of up to 3%. The summary of embodied CO_2 and cost savings for some SCMs has been listed in Table 4.

Table 4: Embodied CO_2 and Cost-Benefit Analysis - Partial Replacement of Cement with Pozzolanic Materials

Mix Material	Total $kgCO_2e/m^3$	%age Saving of $kgCO_2e$ m^3	Cost/m^3 GBP	%age Saving in Cost/m^3
Control Mix with Cement	274	0	323	0
SCM with GGBS 30%	201	27	307	5
SCM with GGBS 45%	165	40	299	8
SCM with GGBS 60%	128	53	290	10
SCM with PFA 10%	247	10	313	3
SCM with PFA 20%	221	19	304	6
SCM with PFA 40%	168	39	285	12
SCM with SF 2.5%	267	2	324	0
SCM with SF 5%	261	5	326	-1
SCM with SF 10%	248	9	328	-2
SCM with MK5%	263	4	321	1
SCM with MK 10%	252	8	318	1
SCM with MK 20%	231	16	313	3
SCM with RHA 2.5%	268	2	321	1
SCM with RHA 5%	262	4	318	1
SCM with RHA 10%	251	9	313	3
SCM with PA 2.5%	268	2	321	1
SCM with PA 5%	262	4	319	1
SCM with PA 10%	251	9	315	3

Note: Positive values show benefits/ savings in reduced CO2 emissions and costs. The negative values show the increased cost.

In contrast, the detailed calculations of embodied CO_2 emissions and cost-benefit analysis have been shown in Table 5 (Appendix I). The use of 1-2% (2-4 kg/m^3) steel fibres, polymer/ polypropylene fibres (PPF), polyethene terephthalate (plastic bottles shredded fibres PETF) and coir (COF) or wheat straw fibres (WSF) are also recommended for small channels/ tunnel lining instead of using steel reinforcement where tensile strength is not the designing requirement. Fibre-reinforced concrete (FRC) will likely impart up to 300% improved tensile strength compared to plain cement concrete (PCC). It can help in controlling/ stopping the creation/ propagation of cracks due to plastic shrinkage/ settlement, thawing/ freezing, long-term drying shrinkage, crazing, improved pore refinement, enhanced impermeability/ post-crack ductility, resistance to spalling/ reinforcement corrosion, reduced alkali-aggregate reaction and further reduction of up to 56% in embodied CO_2 and absorption of 1-2% global waste (Yin et al., 2016; Chaturvedi et al., 2021; Nadir et al., 2022a; Adfil, 2023;

Construction Placements, 2023; Bosun,2023; Ahmed & Nadir, 2024; Nadir et al., 2024). Suppose 10-17% (40-60 kg/m^3) steel fibres (0.75-1 mm, 50 mm long, aspect ratio of 50-67) are used as it is considered a suitable alternative to 1% steel reinforcement with the same shear force resistance and up to 60% bending moment resistance (subject to the structural design considerations, size/ capacity of the channel). In that case, it could further reduce CO_2 emissions by 50% by not using the steel bars for the reinforcement. It could reduce the cost by up to 150%, as investigated in designing steel fibre-reinforced concrete for tunnel lining, with at-par results using 1% steel reinforcement (78 kg steel per m3 of concrete) (Kim & Lee 2021).

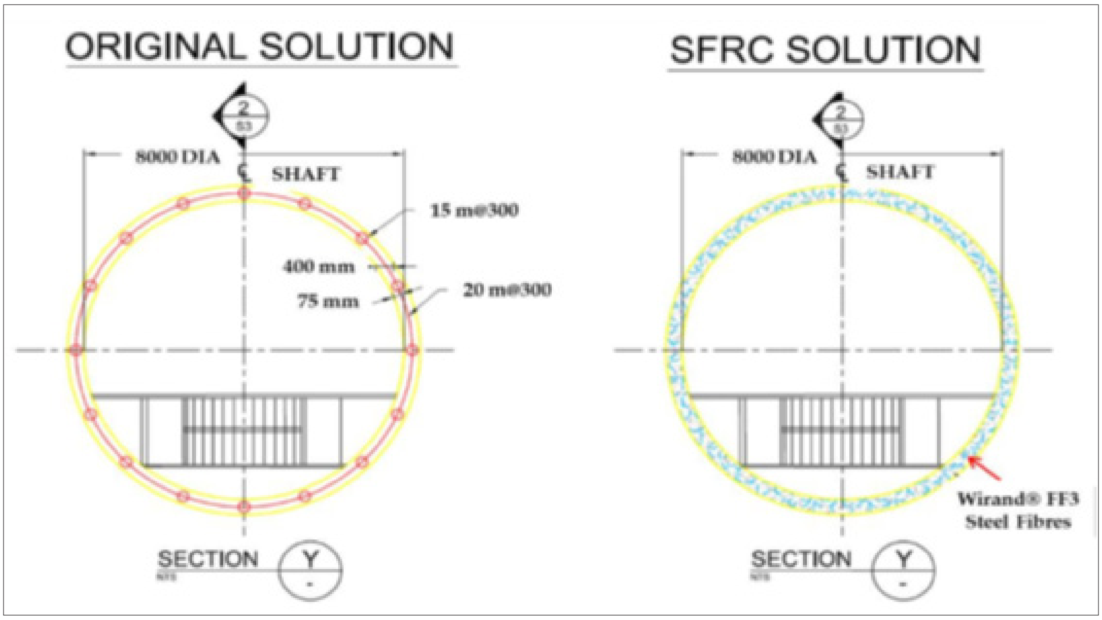


Figure 5: Use STF-Based SCMs in Tunnel Lining (Kim & Lee, 2021).

Conclusions

The construction of hydraulic structures without proper catchment studies results in climatic variations and flooding disasters. To overcome previous hydromodifications/proposed construction, they entail the integration of hydrology/ structural engineering and material sciences. Most greenhouse gas emissions from the construction industry are attributed to cement concrete, the second most used material on earth after water, due to its ease of use, mechanical properties and engineering utilisations. A particular focus on selecting greener material is needed before constructing hydraulic structures/ channel lining due to embodied impacts on the environment and quality. Eco-friendly pozzolanic SCMs with the incorporation of fibres can be used for infrastructure construction, channel lining, and hydro modifications in the water streams with reduced embodied CO_2, lesser ecological impacts and enhanced engineering properties.

References

1. Nadir, H., & Ahmed, A. (2022a). Hydrological Analysis and Statistical Modelling of Swat River Basin for Flood Risk Assessment. *Advances in Earth & Environmental Science, 3*(4), 1-13. https://doi.org/10.47485/2766-2624.1028
2. Nadir, H. M., Ahmed, A. & Moshi, I. (2024). Elucidation of novel, alternative, fiber-reinforced iron-based pozzolanic composites as SCMs. *Academia Materials Science, 1*(3).P1-21. https://www.academia.edu/2997-2027/1/3/10.20935/AcadMatSci7277
3. Nadir, H. M. (2024a). Evaluation of Water Quality and Scarcity Issues for Sustainable Water Management Strategy in Twin Cities of Rawalpindi/ Islamabad, Pakistan. *International Journal of Environment and Geoinformatics (IJEGEO), 11*(3), 076-089. https://doi.10.30897/ijegeo.1487205
4. Nadir, HM., (2024b) A Projected Hydrological Study and Catchment-Level Hydrograph Modelling for Channel Stabilisation. Journal of Earth and Environmental Science Research. SRC/JEESR-299. DOI: doi.org/10.47363/JEESR/2024(6)227”
5. Purnell, P. (2013). The carbon footprint of reinforced concrete. *Advances in Cement Research, 25*(6), pp.362–368. DOI: http://dx.doi.org/10.1680/adcr.13.00013
6. UNEP. (2020). Building sector emissions hit record high, but low-carbon pandemic recovery could help transform sector – UN report. UN Environment. https://www.unep.org/news-and-stories/press-release/building-sector-emissions-hit-record-high-low-carbon-pandemic
7. Lupien, J. R. (2020). Executive Summary. *Asia Pacific Journal of Clinical Nutrition, 11*(1), pp.S97–S97. DOI: https://doi.org/10.1046/j.1440-6047.11.s.6.6.x
8. Obinna, U. (2023). Carbon Footprint of Reinforced Concrete Structures. Structville. https://structville.com/carbon-footprint-of-reinforced-concrete-structures
9. Brander, M., & Davis, G. (2012). Greenhouse Gases, CO_2, CO_2e, and Carbon: What Do All These Terms Mean?. Econometrica. https://ecometrica.com/assets/GHGs-CO2-CO2e-and-

Carbon-What-Do-These-Mean-v2.1.pdf

10. Gagg, C. R. (2014). Cement and concrete as an engineering material, historical appraisal and case study analysis. *Engineering Failure Analysis,* 40, 114-140. DOI: https://doi.org/10.1016/j.engfailanal.2014.02.004
11. Grand view research. (2020). Aggregates Market Size, Share & Trends Analysis Report By Type (Gravel, Crushed Stone, Sand), By Application (Concrete, Road Base & Coverings), By Region (APAC, MEA), And Segment Forecasts, 2020 – 2027. https://www.grandviewresearch.com/industry-analysis/aggregates-market
12. Nadir, H. M., & Ahmed, A. (2021). Impact of Nitrate Vulnerable Zones and Catchment Sensitive Farming on Water Quality in the UK: Case Study of Ingbirchworth and Scout Dyke Reservoirs. *Research & Development in Material Science, 14*(5), 1610-1619. DOI: http://dx.doi.org/10.31031/rdms.2021.14.000848
13. Garside, M. (2022a). Global cement industry – statistics and facts. Statista. https://www.statista.com/topics/8700/cement-industry-worldwide/#topicOverview
14. Garside, M. (2022b). Cement production worldwide from 1995 to 2022. Statista. https://www.statista.com/statistics/1087115/global-cement-production-volume/
15. MPA (2007). Embodied CO2 of UK Cement, additions and cementitious material. Fact Sheet 18 [Part 1]. Mineral Products Association, UK. https://www.concretecentre.com/TCC/media/TCCMediaLibrary/Products/Factsheet_18_2019_updateF.pdf
16. Nadir, H., Ahmed, A., Paul, P., & Mitchell, M. (2022). Potential of Utilising Coir, Straw, and Recycled PET Fibres as Sustainable & Economical Alternative in Fibre Reinforced Concrete. *Research and Developments in Materials Science, 16*(5), 1885-1897. DOI: http://dx.doi.org/10.31031/RDMS.2022.16.000899
17. Synthetex. (2023). Concrete Channel Lining Solutions. https://synthetex.com/erosion-and-scour-solutions/channel-lining/
18. Cemex. (2023). Spray Applied Concrete - Shotcrete Solutions. https://www.cemex.co.uk/sprayed-concrete-shotcrete-solutions
19. Geotechnical Engineering. (2023). Shotcreting. Corporate Acciona. https://www.geotech.net.au/capabilities/slope-stabilisation/shotcreting.html
20. Wikimedia. (2024). Wikimedia. https://www.wikimedia.org/
21. ABM Landscaping, (2023). Civil & Government Rock Pitching Solutions in Perth. Perth Rock Pitching. https://abmlandscaping.com.au/services/rock-pitching/
22. Shirleyana, S. & Anindya, S. A. (2012). The Emergence of Informal Riverside Settlements and Challenges for Planning: The Case of Kali Mas in Surabaya, Indonesia. 3rd International Seminar on Tropical Eco Settlements, Jakarta. https://www.researchgate.net/publication/281765440_the_emergence_of_informal_riverside_settlements_and_challenges_for_planning_the_case_of_kali_mas_in_surabaya_indonesia
23. World Wildlife Fund (WWF). (2012). Living Planet Report 2012: Biodiversity, Biocapacity and Better Choices. https://www.worldwildlife.org/publications/living-planet-report-2012-biodiversity-biocapacity-and-better-choices
24. Prevention Web. (2008). Europe - disaster statistics. http://www.preventionweb.net/english/countries/statistics/index_region.php?rid
25. Flood site. (2009). Flood risk assessment and flood risk management, an introduction and guidance based on experiences and findings of Flood site. http://www.floodsite.net/html/partner_area/project_docs/T29_09_01_Guidance_Screen_Version_D29_1_v2_0_P02.pdf
26. Schleifstein, M. (2011). The Times-Picayune. Mississippi River flooding in the New Orleans area could be massive if the Morganza spillway stays closed. https://www.nola.com/news/weather/
27. Shandana, M. (2012). The Copenhagen Post: Half fear home flooding. http://cphpost.dk/news/half-fear-home-flooding.2106.html
28. Kumar V., (2017). 15 Biggest and Worst Floods Ever in History. Rank Red Science & Technology. https://www.rankred.com/top-10-biggest-and-worst-floods-ever-in-history/
29. National Mississippi River Museum (NMRM). (2018). Explore where history and rivers come alive. http://www.shootforthemoon.com/our_work/river-museum-expansion/
30. WIKI2. (2019). The 2011 Flood in Mississippi River. https://wiki2.org/en/2011_Mississippi_River_floods
31. Kumar, A. (2020). Water Resources and Irrigation Engineering (WRE) CE-603(A). https://lnct.ac.in/wp-content/uploads/2020/03/UNIT-IV-CANALS-AND-STUCTURE-WORD-PDF.pdf
32. US Army Corps of Engineers (USACE). (2024). Upper Mississippi River Restoration (UMRR) Program. https://www.mvr.usace.army.mil/Missions/Environmental-Stewardship/Upper-Mississippi-River-Restoration/
33. Stewart, E. J., Reed, D. W., Faulkner, D. S., & Reynard, N. S. (1999). The FOREX method of rainfall growth estimation I: a review of requirement. Hydrol. *Earth Syst. Sci., 3*(2), 187–195. DOI: http://dx.doi.org/10.5194/hess-3-187-1999
34. Helsel, D. R., & Hirsch, R. M. (2010). Statistical Methods in Water Resources. U.S. Geological Survey Techniques and Methods. https://pubs.usgs.gov/twri/twri4a3/twri4a3.pdf
35. Saleh, A. A. (2011). Developing an empirical formula to estimate rainfall intensity in Riyadh region. *Journal of Engineering Sciences King Saud University, 23*(2), 81-88. DOI: http://dx.doi.org/10.1016/j.jksues.2011.03.003
36. Renard, B., Kochanek, K., Lang, M., Garavaglia, F., Paquet, E., Neppel, L., Najib, K., Carreau, J., Arnaud, P., Borchi, F., Soubeyroux, J.-M., Jourdin, S., Veysseire, J.-M., Sauquet, E., Cipriani, T., Auffray, A. & Aubert, Y. (2013) Data-based comparison of frequency analysis methods: a general framework. *Water Resour Res, 49*(2), 825–843. DOI: https://doi.org/10.1002/wrcr.20087
37. Benameur, S., Benkhaled, A., Meraghni, D., Chebana, F.,

& Necir, A. (2017). Complete flood frequency analysis in Abiod watershed, Biskra (Algeria). *International Society for the Prevention and Mitigation of Natural Hazards, 86*(2), 519–534. https://ideas.repec.org/a/spr/nathaz/v86y2017i2d10.1007_s11069-016-2703-4.html

38. Rowinski, P. M., Strupczewski, W. G., & Singh, V. P. (2002). A note on the applicability of log-Gumbel and log-logistic probability distributions in hydrological analyses: I. Known Available pdf. *Hydrol Sci, J 47*(1), 107–122. DOI: https://www.tandfonline.com/action/showCitFormats?doi=10.1080/02626660209492911
39. Millington, N., Das, S., & Simonovic, S. P. (2011). The Comparison of GEV, Log-Pearson Type 3 and Gumbel Distributions in the Upper Thames River Watershed under Global Climate Models. Water Resources Research Report, 40. https://ir.lib.uwo.ca/wrrr/40/
40. Singo, L. R., Kundu, P. M., Odiyo, J. O., Mathivha, F. I., & Nkunan, T. R. (2013). Flood frequency analysis of annual maximum streamflow for Luvuvhu River catchment, Limpopo Province, South Africa. University of Venda. https://univendspace.univen.ac.za/server/api/core/bitstreams/e9eb091d-4bfe-48d4-8acf-e4eab36d1670/content
41. Bezak, N., Brilly, M., & Sraj, M. (2014). Comparison between the peaks-over threshold method and the annual maximum method for flood frequency analysis. *Hydrol Sci J, 59*(5), 959–977.
DOI: https://doi.org/10.1080/02626667.2013.831174
42. Oke, M. O. & Aiyelokun, O. A. (2015). Statistical Approach to Flood Disaster Management and Risk Reduction in Ibu River Basin. *Nigerian Journal of Technological Research, 10*(2), 17. DOI: http://dx.doi.org/10.4314/njtr.v10i2.4
43. Saghafian, B., Golian, S., & Ghasemi, A. (2014). Flood frequency analysis based on simulated peak discharges. *Nat Hazards, 71*(1), 403–417.
https://ideas.repec.org/a/spr/nathaz/v71y2014i1p403-417.html
44. Deng, X., Ren, W., & Feng, P. (2016). Design flood recalculation under land surface change. *Journal of the International Society for the Prevention and Mitigation of Natural Hazards, 80*(2), 1153–1169. https://ideas.repec.org/a/spr/nathaz/v80y2016i2p1153-1169.html
45. Kamal, V., Mukherjee, S., Singh, P., Sen, R., Vishwakarma, C. A., Sajadi, P., Asthana, H. & Rena, V. (2016). Flood frequency analysis of Ganga River at Haridwar and Garhmukteshwar. *Applied Water Science, 7*(4), pp.1979–1986. DOI: http://dx.doi.org/10.1007/s13201-016-0378-3
46. Rulfova, Z., Buishand, A., Roth, M., & Kysely, J. (2016). A two-component generalised extreme value distribution for precipitation frequency analysis. *J Hydrol*, 534, 659–668. DOI: https://doi.org/doi:10.1016/j.jhydrol.2016.01.032
47. Mathwave Easy Fit 5.6 Pro (2019): 1-month Trial version provided by www.mathwave.com
48. Liu, Y., Liu, H., Chen, Y., Gang, C. & Shen, Y. (2022). Quantifying the contributions of climate change and human activities to vegetation dynamics in China based on multiple indices. *Science of The Total Environment, 838*(4), pp.156553–156553.
DOI: https://doi.org/10.1016/j.scitotenv.2022.156553
49. Cunnane, C. (2010). Statistical distributions for flood frequency analysis. *J Hydraul Res, 28*(5), 650.
50. Jena, J. & Nath, S. (2019). An Empirical Formula for Design Flood Estimation of Un-Gauged Catchments in Brahmani Basin, Odisha. *Journal of The Institution of Engineers (India): Series A, 101*(14), pp.1–6.
DOI: http://dx.doi.org/10.1007/s40030-019-00402-x
51. Adeyi, G. O., Adigun, A. I. , Onyeocha, N. C., Okeke, O. C. (2020). Unit Hydrograph: Concepts, Estimation Methods and Applications in Hydrological Sciences. *IJESC, 10*(6), 26211-26217. https://www.researchgate.net/publication/344596311_Unit_Hydrograph_Concepts_Estimation_Methods_and_Applications_in_Hydrological_Sciences
52. Iresh, A. D. S., Athapattu, B. C. L., Obeysekera, J., & Fernando, W. C. D. K. (2024). Floodplain Zoning and Mapping for Lower Kelani River, Sri Lanka. *Engineer Journal of the Institution of Engineers Sri Lanka, 57*(3), pp.23–33.
DOI: https://doi.org/10.4038/engineer.v57i3.7594
53. Iresh, A. D. S., Dilthara, G. W. A. S. & Sugeeshwara, S. P. C. (2024). Estimation of Catchment Parameters of Snyder's Synthetic Method for Water Resources Planning and Flood Management in Sri Lanka. *Engineer Journal of the Institution of Engineers Sri Lanka. ENGINEER, 57*(2), pp.81–86. https://engineer.sljol.info/articles/7595/files/66404285560e6.pdf
54. Shashika, D., Obeysekera, J., Athapattu, B. C. L. & Fernando, W. C. D. K. (2024). Rainfall Intensity–Duration–Frequency Curves Using Cluster and Regional Frequency Analyses. *Journal of Hydrologic Engineering, 29*(5).
DOI: https://doi.org/10.1061/JHYEFF.HEENG-6167
55. Gnilsen, R. (1987). Plain Concrete Tunnel Lining-Design Concepts. *TRANSPORTATION RESEARCH RECORD.* https://onlinepubs.trb.org/Onlinepubs/trr/1987/1150/1150-003.pdf
56. Leika et al., (2000). DESIGN OF SPRAYED CONCRETE FOR UNDERGROUND SUPPORT. https://tunnel.ita-aites.org/media/k2/attachments/public/recommendations%20AFTES%20sprayed%20concrete.pdf
57. UK Centre for Ecology & Hydrology. (2022). Flood Estimation Handbook (FEH).
https://www.ceh.ac.uk/services/flood-estimation-handbook
58. FSU, (2012). Flood studies and update programme. https://opw.hydronet.com/data/files/FSU%20Work%20Package%204_2.pdf
59. UK Centre for Ecology & Hydrology. (2013). Flood Estimation Handbook Web Service.
https://fehweb.ceh.ac.uk/
60. Memon, A.A., Leghari, K.Q., Agha, Khatri, K.L., Syed Attique Shah, Pinjani, K.K., Soomro, R. and Ansari, K. (2013). Design and Evaluation of Dadu Canal Lining for Sustainable Water Saving. *Journal of Water Resource and Protection, 5*(7), pp.689–698. DOI: https://www.scirp.org/journal/paperinformation?paperid=33647
61. National River Flow Archive (NRFA). (2015). How are

Flows Measured?. https://nrfa.ceh.ac.uk/how-are-flows-measured

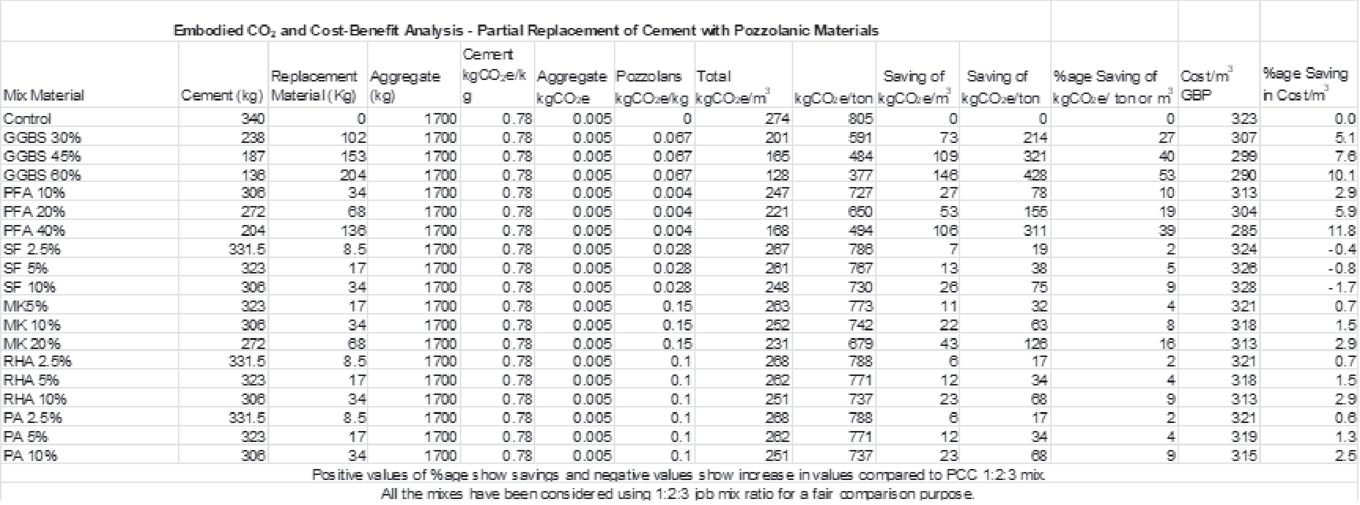
62. Bakhshi, M. & York, N. (2016). DESIGN OF FIBER-REINFORCED TUNNEL SEGMENTAL LINING ACCORDING TO NEW ACI REPORT. RESILIENT INFRASTRUCTURE. https://core.ac.uk/download/pdf/61694293.pdf
63. Open Channels. (2016). Chapter 5 - Open Channels. County of Roanoke. https://www.roanokecountyva.gov/DocumentCenter/View/7709/Ch-5-Open-Channels---2016-Design-Manual
64. Virginia Department of Transportation. (2002). Chapter 7 -Ditches and Channels. Drainage Manual. https://www.vdot.virginia.gov/media/vdotvirginiagov/doing-business/technical-guidance-and-support/technical-guidance-documents/location-and-design/migrated/drainagemanual/chapter7_acc10172023_PM.pdf
65. Section 44. (2016). Section 44 -shotcrete, cast concrete channel lining, and grouted cobble. https://saccountyspecs.saccounty.gov/Documents/PDF%20Documents%202016/Specifications/Section%2044.pdf
66. The Constructor. (2018). Canal Linings - Types and Advantages. https://theconstructor.org/water-resources/canal-linings-types-advantages/11052/
67. CCLD. (2019). CONCRETE CHANNEL LINING DETAILS N/A. https://www.fusedind.com/wp-content/uploads/2019/11/Concrete-Channel-Lining-Details.pdf
68. The Engineering Toolbox. (2019). Manning's Roughness Coefficients. https://www.engineeringtoolbox.com/mannings-roughness-d_799.html
69. United States Department of Agriculture (USDA). (2020). Irrigation ditch lining. https://www.nrcs.usda.gov/sites/default/files/2022-09/Irrigation_Ditch_Lining_428_NHCP_CPS_2020.pdf
70. GOV.UK. (2021). Fluvial design guide. https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/fluvial-design-guide
71. Waqas-Chaudhry. (2021). What Is Channel Lining? Which types of lining are mostly used?. Civil Rack. https://civilrack.com/construction/channel-lining/
72. FEG. (2022). Guidance Flood estimation guidelines. Environment Agency. https://www.gov.uk/government/publications/flood-estimation-guidelines
73. Scribd. (2015). Application of Unit Hydrograph To Derive Runoff Hydrograph. Hydrology. https://www.scribd.com/document/394224482/Application-of-Unit-Hydrograph-to-Derive-Runoff-Hydrograph
74. Kim, M. S. & Lee, S. S. (2021). Design Study of Steel Fibre Reinforced Concrete Shaft Lining for Swelling Ground in Toronto, Canada. *Applied Sciences, 11*(8), p.3490. DOI: https://doi.org/10.3390/app11083490
75. United States Department of Agriculture. (2022). Natural Resources Conservation Service CONSERVATION PRACTICE STANDARD LINED WATERWAY OR CONVEYANCE CHANNEL CODE 468. NHCP. https://www.nrcs.usda.gov/sites/default/files/2022-12/468-NHCP-CPS-Lined-Waterway-or-Conveyance-Channel.pdf
76. Doston, J., (2020). How to Calculate Exceedance Probability. Sciencing https://sciencing.com/calculate-exceedance-probability-5365868.html
77. US Geological Survey (USGS). (2016). Water Science School. https://www.usgs.gov/special-topics/water-science-school
78. Chegg. (2023). Using the Rational formula Q = (CIA) / 3.6, and with reference to the drainage reference data in the Appendices, calculate the peak storm water runoff for a catchment. https://www.chegg.com/homework-help/questions-and-answers/1-using-rational-formula-q-cia-36-reference-drainage-reference-data-appendices-calculate-p-q51245994
79. IS: 3873- 19192. (1993). Laying cement concrete/ stone slab Lining on canals – code of practice. Bureau of Indian Standards. https://archive.org/details/gov.in.is.3873.1993
80. Thomason, C. (2019). Hydraulic Design Manual Manual: Hydraulic Design Manual. http://onlinemanuals.txdot.gov/TxDOTOnlineManuals/TxDOTManuals/hyd/hyd.pdf
81. Highway Design Manual. (2020). CHAPTER 860 -ROADSIDE CHANNELS Topic 861 -General. https://dot.ca.gov/-/media/dot-media/programs/design/documents/chp0860-a11y.pdf
82. Yorkshire Dales National Park. (2024). River Swale. https://www.yorkshiredales.org.uk/places/river_swale/
83. Yorkshire Dales Rivers Trust. (2024). The River Swale. https://www.ydrt.org.uk/home-2/river-swale/
84. Walks in Yorkshire. (2024). Circular walk from Richmond along the River Swale and via Easby Abbey. https://www.daleswalks.co.uk/walks/river-swale-and-easby-abbey-from-richmond/
85. Swale Way Google Maps. (2024). Google My Maps. https://www.google.com/maps/d/u/0/viewer?mid=1aInWBYAI0Q06NqQM0cUdYVZdJREWVXsc&femb=1&ll=54.28152159259802%2C-1.8355739545999983&z=10
86. Nadir, H. M., Ahmed, A., Asher, M., Goodwin, C., Kenyon, O., Rogers, L., & Routledge, C. (2024). Strategic Integration of Catchment Level Natural and Structural Methods of Sustainable Flood Management: A Case Study of River Wharfe Catchment Area. *Adv Earth & Env Sci, 5*(2), 1-11. DOI: https://doi.org/10.47485/2766-2624.1043
87. Team, D. (2018). Steel Requirements for RCC Beam, Column, Slab, Foundation, & Lintel. DAILY CIVIL. https://dailycivil.com/steel-requirements-rcc-beam-column-slab-foundation-lintel-1/
88. Institution of Civil Engineers (ICE). (2011). Energy Briefing Sheet: Embodied Energy and Carbon. https://www.ice.org.uk/media/w4kjrruf/embodied_energy_and_carbon.pdf
89. Yin, S., Tuladhar, R., Riella, J., Chung, D., Collister, T., Combe, M. & Sivakugan, N. (2016). Comparative evaluation of virgin and recycled polypropylene fibre reinforced concrete. *Construction and Building Materials*, 114, pp.134–141. DOI: https://doi.org/10.1016/j.conbuildmat.2016.03.162
90. Chaturvedi, R., Singh, P. K. & Sharma, V. K. (2021).

Analysis and the impact of polypropylene fibre and steel on reinforced concrete. *Materials Today: Proceedings, 45*(2), pp.2755–2758. DOI: https://doi.org/10.1016/j.matpr.2020.11.606

91. ADFIL Construction Fibres. (2023). Adfil construction fibres. Properties of Polypropylene by Synthetic Fibres. https://adfil.com/gb-en/about-us
92. Construction Placements. (2023). Fiber Reinforced Concrete: A Sustainable Building Material for the Future. Construction Placements. https://www.constructionplacements.com/fiber-reinforced-concrete-frc/
93. Bosun, (2023). Bosun Precast Water Channel Linings and V-Drain Channels. https://www.bosun.co.za/products/erosion-control/bosun-precast-water-channel-linings-and-v-drain-channels/
94. Flood Break Revolutionary Flood Control. (2012). Hospital Featured in FEMA Flood proofing Publication. Flood Break Automatic Flood Barriers. https://floodbreak.com/hello-world/
95. Fakhris. (2023). Erosion-Control-or-River-Slope-Control-Blocks. https://fakhris.com/view-product/5
96. Flood Protection Bunds and Gabions (2023). www.pixshark.com
97. Glazzard, P. (2007). River Wharfe Weir at Tadcaster. https://check-for-flooding.service.gov.uk/station/8202
98. Haan, C. T. (1977). Statistical Methods in Hydrology. Iowa State University Press. https://books.google.co.in/books/about/Statistical_Methods_in_Hydrology.html?id=M903vgAACAAJ&redir_esc=y
99. Han, X., Wang, X., Zhu, Y., Huang, J.-S., Yang, L., Chang, Z. & Fu, F. (2020). An Experimental Study on Concrete and Geomembrane Lining Effects on Canal Seepage in Arid Agricultural Areas. *Water, 12*(9), pp.2343–2343. DOI: https://doi.org/10.3390/w12092343
100. Holt, R. D., Barfield, M. & Peniston, J. H. (2022). Temporal variation may have diverse impacts on range limits. *Philosophical Transactions of the Royal Society B: Biological Sciences, 377*(1848). DOI: https://doi.org/10.1098/rstb.2021.0016
101. Kjeldse, T. R., Jones, D. A. & Bayliss, A. C. (2008). Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme Improving the FEH statistical procedures for flood frequency estimation Science Report: SC050050. *Environment Agency*. https://assets.publishing.service.gov.uk/media/602e5c0f8fa8f54331b080e6/Improving_the_FEH_Statistical_Procedures_for_Flood_Frequency_Estimation_Technical_Report.pdf
102. McKee, R. D. (2020). Hiking the Coast to Coast. Apple Books. https://books.apple.com/gb/author/roy-d-mckee/id1520017621
103. Roy, D. K. & Sil, A. (2012). Effect of Partial Replacement of Cement by Silica Fume on Hardened Concrete. *International Journal of Emerging Technology and Advanced Engineering, 2*(8), 472-475. https://www.researchgate.net/publication/305768329_Effect_of_Partial_Replacement_of_Cement_by_Silica_Fume_on_Hardened_Concrete
104. Abdu, T., Ibrahim, T-E. G. & Abdel-Magid, I. M. (2011). Design Considerations of Concrete Lined Channels: Experience of Rawakeeb Research Station. Sudan Academy of Sciences Journal, 4, 1-16. https://www.researchgate.net/publication/271964823_Design_Considerations_of_Concrete_Lined_Channels_Experience_of_Rawakeeb_Research_Station
105. Team, G. (2023). Channel Lining: Material dan Perencanaannya - Geosinindo. Tetrasa Geosinindo. https://www.geosinindo.co.id/post/channel-lining-fungsi-jenis-material-dan-perencanaannya
106. Tofiq, F. & Guven, A. (2015). Optimal design of trapezoidal lined channel with least cost: Semi-theoretical approach powered by genetic programming. *Water SA, 41*(4), p.483. DOI: https://doi.org/10.4314/wsa.v41i4.07
107. Wikipedia. (2024). River Swale. Wikipedia. https://en.wikipedia.org/wiki/River_Swale#/media/File:Swale_(rivi%C3%A8re).png
108. Concrete canvas. (2023). Concrete canvas Channel Lining. https://www.concretecanvas.com/uploads/CC-Channel-Lining-HS2-Compound-0-UK-1.pdf
109. Geograph. (2023). Coastal protection © Graham Horn cc-by-sa/2.0. https://www.geograph.org.uk,2023/photo/1897792, Pyramid breakwater stones with Raised berms/ walls and edges (https://www.geograph.org.uk, 2023/photo/1897792). [Accessed 2 October 2023].

Appendix I

Table 5: Detailed Calculations of Embodied CO2 and Cost-Benefit Analysis – Partial Replacement of Cement with Pozzolanic Materials (SCMs)



Embodied CO_2 and Cost-Benefit Analysis - Partial Replacement of Cement with Pozzolanic Materials

Mix Material	Cement (kg)	Replacement Material (Kg)	Aggregate (kg)	Cement $kgCO_2e/kg$	Aggregate $kgCO_2e$	Pozzolans $kgCO_2e/kg$	Total $kgCO_2e/m^3$	$kgCO_2e/ton$	Saving of $kgCO_2e/m^3$	Saving of $kgCO_2e/ton$	%age Saving of $kgCO_2e$/ ton or m^3	Cost/m^3 GBP	%age Saving in Cost/m^3
Control	340	0	1700	0.78	0.005	0	274	805	0	0	0	323	0.0
GGBS 30%	238	102	1700	0.78	0.005	0.067	201	591	73	214	27	307	5.1
GGBS 45%	187	153	1700	0.78	0.005	0.067	165	484	109	321	40	299	7.6
GGBS 60%	136	204	1700	0.78	0.005	0.067	128	377	146	428	53	290	10.1
PFA 10%	306	34	1700	0.78	0.005	0.004	247	727	27	78	10	313	2.9
PFA 20%	272	68	1700	0.78	0.005	0.004	221	650	53	155	19	304	5.9
PFA 40%	204	136	1700	0.78	0.005	0.004	168	494	106	311	39	285	11.8
SF 2.5%	331.5	8.5	1700	0.78	0.005	0.028	267	786	7	19	2	324	-0.4
SF 5%	323	17	1700	0.78	0.005	0.028	261	767	13	38	5	326	-0.8
SF 10%	306	34	1700	0.78	0.005	0.028	248	730	26	75	9	328	-1.7
MK5%	323	17	1700	0.78	0.005	0.15	263	773	11	32	4	321	0.7
MK 10%	306	34	1700	0.78	0.005	0.15	252	742	22	63	8	318	1.5
MK 20%	272	68	1700	0.78	0.005	0.15	231	679	43	126	16	313	2.9
RHA 2.5%	331.5	8.5	1700	0.78	0.005	0.1	268	788	6	17	2	321	0.7
RHA 5%	323	17	1700	0.78	0.005	0.1	262	771	12	34	4	318	1.5
RHA 10%	306	34	1700	0.78	0.005	0.1	251	737	23	68	9	313	2.9
PA 2.5%	331.5	8.5	1700	0.78	0.005	0.1	268	788	6	17	2	321	0.6
PA 5%	323	17	1700	0.78	0.005	0.1	262	771	12	34	4	319	1.3
PA 10%	306	34	1700	0.78	0.005	0.1	251	737	23	68	9	315	2.5

Positive values of %age show savings and negative values show increase in values compared to PCC 1:2:3 mix.

All the mixes have been considered using 1:2:3 pb mix ratio for a fair comparison purpose.