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Sustainable utilization of calcined granite powder as partial replacement for cement in concrete mixtures: A mechanical and environmental assessment

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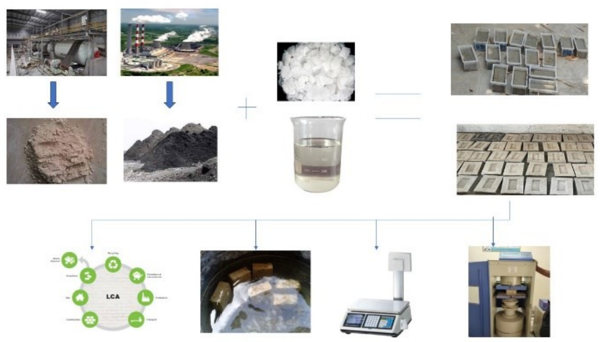
Graphical abstract



Abstract

The escalating environmental concerns associated with cement production have prompted to explore alternative materials for partial replacement, aiming to reduce the carbon footprint of the construction industry. This research investigates the incorporation of calcined granite powder, a byproduct of granite processing, as a sustainable supplementary cementitious material. The granite powder, which is conventionally disposed of in landfills, was collected directly from the industry and subjected to calcination to enhance its pozzolanic properties. The experimental investigation involved replacing cement with calcined granite powder in varying proportions (0-50%) in concrete mixes of M30 grade. Mechanical properties such as compressive strength, flexural strength, and durability were assessed to evaluate the performance of the formulated mixes. Remarkably, the mix containing 70% cement and 30% calcined granite powder exhibited a substantial increase in compressive strength by 7 %, flexural strength by 11 % and 13 % increase in tensile strength compared to the conventional M30 mix. Furthermore, a life cycle assessment (LCA) was conducted using SimaPro software to analyze the environmental impact of the formulated concrete mixes. The results indicated that the concrete mix with 30% calcined granite powder and 70% cement not only demonstrated superior mechanical properties but also proved to be environmentally sustainable, exhibiting reduced global warming potential. This finding underscores the potential of calcined granite powder as a viable and eco-friendly alternative, contributing to the sustainable evolution of concrete production.

Keywords: Cement; Granite Powder; Concrete; Compressive strength; Life cycle assessment; Sustainability

1. Introduction

Sustainable concrete has become the state of the art study by the various researchers across the world. With the industries established all across the world have paved the way to incorporate the wastes that were getting released as by-products in concrete as partial replacement to cement. One such a material is granire waste that gets released out of the Granite Industry.

India's production of Granite is very abundant and stood first among the different countries to export it to other countries like USA, Europe etc.(Chajec., 2021). The total reserves of Granite in India as per IBM is around 16357680 tons in 2021. The major contributors are Andhra Pradesh, Rajasthan and Karnataka (Rojo-López *et al.* 2020). As the stone gets dressed in the industry, results in the release of waste. Industries are now facing the problems to dispose the waste to landfill sites in the suitable manner. The Granite dust causes environmental pollution in terms of air pollution and ground pollution. GWD (Granite waste dust) eventually settles down on the vegetation and crops around the granite processing industries and threatens the ecology of the environment. It is high time to concentrate on this phenomenon and avoid the destruction caused by adopting feasible and suitable mechanisms of solid waste management (Gao., *et al.* 2017, Lu *et al.* 2018, Silva *et al.* 2013.). One mechanism which is found feasible and has scope is incorporating Granite waste as supplementary cementitious materials as partial replacement to cement in concrete. Experimental investigations were carried out to study the effect of incorporating Granite waste as partial replacemebt to cement on the mechanical properties and durability performance. (Ghannam *et al.* 2016, Jain *et al.* 2019, Binici *et al.*2008.). In the study carried out to investigate the effect of incorporation of Granite dust on the mechanical properties of cement composites, attention was paid particular to the properties of granite powder grains (Mashaly *et al.* 2018, Qian *et al.* 2020, Amin *et al.* 2017, Nepomuceno *et al.*2012), which was from the investigation found that the the property has significant effect on the mechanical performance of the cement composite matrix. With different studies carried out to determine the feasibility of utilsation of Granite waste as partial replacement to cement, it was observed that the granite waste has the ability to participate in the hydration process along with cement at later ages (Vijayalakshmi and Sekar, 2013, Sadek *et al.* 2016, Gupta and Vyas, 2018, Li *et al.* 2013, Elyamany *et al.* 2014). It was also observed that the compressive strength of the formulated cement blended composites was in par with the conventional mix at later ages. From an investigation caried out in determining the effect of granite powder on the microstructure of the blended cement composites, itw as observed that the granite powder acts a filler in the early ages [Praseeda and Rao., 2021, Praseeda and Rao., 2022). As a filler it first fills the voids in the composite matrix creating a significant impact on the structure by decreasing the porosity and thereby also plays a crucial role pertaining thr durability of the composites developed. When the granite dust was examined for its impact on the durability performance in terms of water absorption, sulphate attack, abrasion, and freeze-thaw resistance, it was observed that the replacement of cement upto 20 % by the material showed significant improvement in the durability in term sof water absoption. The same percentage replacement also enhance the properties of the cement composites by making them resistance against the abrasion loss, sulphate attack and freeze-thaw [Dandu and Rao., 2024, Mehmood., 2023). From the observations made by the researchers pertaining to the effect of Granite Dust on the perfromnace of the blended cement composites, it was understood that the filling of the voids in the matrix of the composite resulting in the reduction of the connectivity of capillary pores may be the reason for enhancement in the durability performance of the developed cement blended composites. When the Granite dust and Marble dust incorporated cement composites were evaluated for the resistance against the corrosyion effect, the replacemebt of cement by 20–30% cement with both MD and GD improved the resistance against corrosion. This enhancement may be attributed to the voids filling ability of the material, which in turn shows a noticeable effect on the properties of the composite to a large extent when compared to the conventional mixes. (Mehmood *et al.* 2024, Nair and Viswanathan.,2023, Ramadi et al. 2020)).

In the present experimental investigation carried out to determine the effect of calcined granite waste on the mechanical performance of concrete. The waste that is being released out of the Granite Industry is very much prone to the environmental pollution in addition to the human health. To avoid any of the two phenomena to occur, possible solution may be the incorporation of the same in the development of the blended cement composites wherein the cement is partially replaced by the Granite waste. The results obtained from the work shows a significant impact as the material can be used effectively used avoiding any of the problems caused to the environment such as in reducing the disposal of the material to a certain extent. The work emphasizes on the detemination of the physical and chemical aspects of the granite dust utilsed from the industry, mechanical performance of the cement compoistes developed by raplacing the cement partially with Granite dust and the sustainability of the developed mixes and its comparison with the conventional mix.

The novelty of the study is to incorporate the granite powder subjected to calcination as partial replacement to the cement in concrete. Also Life cycle assessment was carried out to compare it with the conventional concrete so as to draw the significance of utilization of the waste as a source of new material as partial replacement to the cement.

2. Experimental Program

2.1. Materials

2.1.1. Cement

Ordinary Portland cement of 53 grade conforming to IS 12269-1987 has been used in the present study. From the physical analysis, the gravity of the cement was found to be 3.14. The chemical composition of the cement obtained from XRF analysis is presented in the **Table 1**. Morphology of the cement detemined using SEM is presented in **Figure 1**. The particle size analysis for cement is presented in **Figure 2**. The results obtained from the analysis are presented. The physical properties of cement are presented in **Table 2**.

Cement $\boldsymbol{D}_{10} = 3.46\,\mu\text{m}, \boldsymbol{D}_{50} = 16.71\,\mu\text{m}, \boldsymbol{D}_{90} = 44.52\,\mu\text{m}$

Table 1. Chemical composition results of OPC

Constituent	Result
SiO_2	21.18 %
Al_2O_3	5.05 %
Fe_2O_3	4.11 %
CaO	55.27 %
MgO	0.22 %
SO_3	0.55 %
K_2O	0.57 %
Na_2O	0.34 %
Loss on ignition	0.42%

Table 2. Physical properties of the cement

Property	Result
Fineness (weight of residue left on 90 micron sieve)%	1.74
Specific gravity	3.14
Normal Consistency %	30
Initial setting time (minutes)	104
Final setting time (minutes)	570

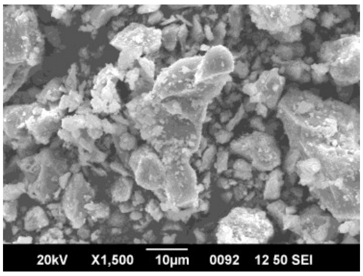


Figure 1. SEM image of cement

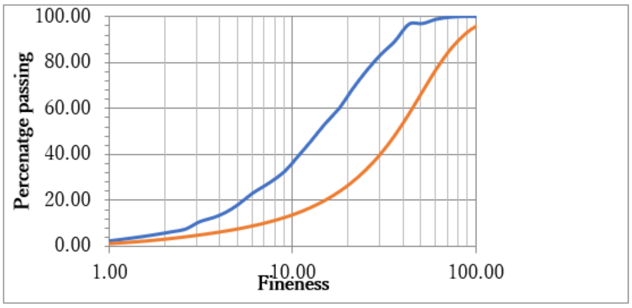


Figure 2. Particle size analysis for cement and Granite waste powder

2.1.2. Granite waste powder

Granite powder was which was utilized in the present investigation was collected from the one of the Granite industry in Hyderabad. The chemical composition of the Granite waste analysed by the XRF method is presented in **Table 3**. As pet ASTM C 618, the chemical composition of the material to be utilized as a pozzolanic material should contain the total amount of silicon dioxide, aluminum trioxide and ferrous oxide to be about 82 %. Owing to the specif surface area of the Granite powder which was found to be 32 m^2/g, it was found to be feasibile for utilization as supplementary cementntiitous material in concrete as partial replacement to cement. The particle size analysis is presented in **Figure 2** aln with the SEM image of Granite waste powder in **Figure 3**.

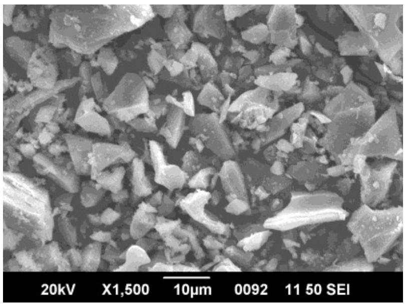


Figure 3. SEM image of Granite waste powder

Table 3. Chemical composition of Granite waste and cement

Constituent	Granite waste powder	Cement
SiO_2	69%	18.6
Al_2O_3	16.5%	3.77
Fe_2O_3	0.5%	4.03
CaO	0.5%	66.3
MgO	1.25%	2.13
SO_3	1.23%	2.67
K_2O	3.2%	0.46
Na_2O	2.12%	1.39
Loss on ignition	1%	0.64

2.1.3. Fine aggregate

The river sand with its gradation determined as per IS 383:2016 falling into zone-II has been used in the present study as the fine aggregate. The specific gravity was found to be 2.66 with fineness modulus of 2.6. The physical properties and gradation of the fine aggregate were presented in **Table 4**. Fine aggregate which is used is checked for the presence of deleterious substances and organic and inorganic matter. The sand was air dried before its incorporation to avoid bulking effect.

Table 4. Gradation and physical properties of fine aggregate

Sieve size (mm)	% passing
80	100
40	100
20	100
10	100
4.75	94.4
2.36	90.6
1.18	75.8
0.6	54.7
0.3	22.6
0.15	3.3
Physical Properties	
Fineness modulus	2.6
Specific gravity	2.66
Bulk density	1615.83 kg/m^3
Absorption	2.72 %

2.1.4. Coarse aggregate

Granite with dark blue in colour, angular in shape with specific gravity of 2.89 is used as coarse aggregate. Gradation and the physical properties of the coarse aggregate are presented in the **Table 5**. For the present experimental investigation aggregate of size 20 mm size has been used.

Table 5. Gradation and physical properties of coarse aggregate

Sieve size (mm)	**% passing**
80	100.00
40	100.00
20	95.50
10	4.35
4.75	0
2.36	0
1.18	0
0.6	0
0.3	0
0.15	0
Physical Properties	
Fineness modulus	6.72
Specific gravity	2.89
Bulk density	1562.8 kg/m^3
Absorption	0.4 %

2.1.5. Superplasticisers

Conplast SP430 is used as a superplasticising admixture which reduces the water usage in the development of the concrete mixes. The specific gravity of the liquid is 1.18 and resembles brown colour and it conforms to BS 5075, BS: EN 934-2 and ASTM C494 as Type A and Type F. The advantage of using this superplasticiser is the improved cohesion and particle dispersion and minimises segregation and bleeding and improves workability. Mainly it has been incorporated in the study to reduce water content without compromising on the workability. In order to achieve the design workability and to allow the production of high strength concrete without excessive cement and water content, Conplast SP 430 has been used. With its usage in the study, it was found to improve the workability of the concrete without increasing water demand. The dosage of super plascticiser was kept constant through out the experimental work. It was added at a dosage percentage of 0.1 % by weight of binder content.

2.2. Mixing procedure

The coarse aggregate of the measures quantity was fed into the pan mixture flowed by fine aggregate and cementitious material (Cement and calcined granite waste). The dry ingredients were mixed thoroughly and water was added. The mixing was carried out till the homogenous mixture was obtained. SP 430 in the required dosage was added to increase the workability of concrete. The proportions were tabulated in the **Table 6**. The water cement ration adopted for M 30 grdae concrete is 0.45.

Table 6. Proportioning of Materials for casting

Mix designation	Cement kg/m^3	Calcined Granite waste kg/m^3	River sand kg/m^3	Coarse aggregate kg/m^3	water l/m^3
MC	380	0	540	1240	171
MCG1	190	190	540	1240	171
MCG2	228	152	540	1240	171
MCG3	266	114	540	1240	171
MCG4	304	76	540	1240	171
MCG5	342	38	540	1240	171

Table 7. Inventory data for 1 m^3 concrete production

Description	OPC	MCG1	MCG2	MCG3	MCG4	MCG5
Cement	380	190	228	266	304	342
Calcined granite waste	0	190	152	114	76	38
Fine aggregate	540	540	540	540	540	540
Coarse aggregate	1240	1240	1240	1240	1240	1240
Sand	596	596	596	596	596	596
Super plasticiser	1.14	1.90	2.28	2.66	3.04	3.42

Table 8. Type of transportation and distance of transportation of materials

Types of raw materials	Route		Type of transport	Transportation distance (km)
	From	To		
Cement	Cement vendor	VNR VJIET	8	7.5-16 t
Calcined granite waste	Granite factory	VNR VJIET	26	7.5-16 t
Fine aggregate	Quarry site	VNR VJIET	7	7.5-16 t
Coarse aggregate	Quarry site	VNR VJIET	7	7.5-16 t
Super plasticiser	Chemical vendor	VNR VJIET	25	7.5-16 t

2.3. Casting of specimens

The mixture from pan mixture was collected in a tray. The specimens of 150 × 150 × 150 mm were filled with the mixture for determining the compressive strength of concrete. Similarly the specimens of size 100 × 100 × 500 mm were filled to determine the flexural strength and 150 mm dia and 300 mm length specimens to determine the split tensile strength of the concrete. For each of the formulated mix, three sets of specimens were cast. Upon testing the average value of the three specimens was considered.

2.4. Tests conducted

2.4.1. Compressive strength

As per IS 516:2021 [32], Compression was conducted on the specimens cast with the proportioned mixes. 150 × 150 × 150 mm cubes were cast. Three cubes for each of the mix were cast. After 24 hours, the specimens were demoulded and immersed in curing tank. The cubes were taken out of the water tank at specified time period and tested for compressive strength in compression testing machine. Th applied rate of loading is 140 kg/cm^2 /min as per the code applied load perpendicular to the surface of specimen. Load at failure for the three specimens is noted and strength is calculated. The average of the three values is reported as the compressive strength for the mix cast.

2.4.2. Flexural strength

The prisms of dimensions 100 × 100 × 500 mm were cast and tested for flexural strength as IS 516: in a universal testing machine of 20 tones capacity. Three prisms for each of the mix were cast. In total Eighteen prisms were cast for the control mix and mix with cement, Granite dust along with coarse aggregate and fine aggregate. The three prisms were tested after which depending upon the line of fracture from the nearest end, the formulae is adopted to calculate the flexural strength expressed in terms of modulus of rupture f_b. The results obtained for each of the prisms was recorded and average of the three values was taken s the final values and reported.

2.4.3. Split tensile strength

As per IS 5816:1999, cylindrical mould of diameter not less than four times the size of the coarse aggregate or not less than 150 mm is used. As per the provisions provided cylinder of size 150 mm dia and 300 mm length was used to cast the specimens of the proportioned mixes. The cylindrical moulds of diameter 150 mm and length 300 mm were used to cast the specimens for the test. The cast specimens were immersed in water tank for curing. At the end of the specified curing period, the cylinders were taken out and tested under a universal testing machine by applying a load of within the range 1.2 N/ (mm^2/min) to 2.4 N/ (mm^2/min). The obtained load at failure is considered and the spiltting tensile strength of the specimen is calculated. The average of the three values is taken and recorded as the spiltting tensile strength of the mix.

2.5. Comparative LCA approach

The environmental impact of utilizing of calcined granite powder as partial replacement for cement in concrete was assessed through a life cycle assessment as per ISO 14044:2006. The primary goal of this assessment was to examine the feasibility of utilizing calcined granite powder as binder replacement for cement. This substitution aimed to achieve environmental benefits without compromising the concrete's desired technical performance. The life cycle assessment considered various factors, including the production of calcined granite powder, super plasticizer, energy consumption, and CO_2 emissions. The functional unit chosen for this study was 1 m3 of concrete. The study's system boundary encompassed the entire product life cycle, from the cradle to the gate. **Figures 4 and 5** delineated the corresponding system boundaries. **Table 7** depicted the life cycle inventory of the formulated concrete mix proportions for functional unit.

Furthermore, **Table 8** outlines the specific transportation mode and the actual distance covered from the raw material sources to the experimental site. The quantification of impact categories was carried out using Sima Pro LCA software. Data for material and energy flows, integral to this study, were sourced from various outlets such as published literature, industry firms, and databases. The Eco-invent database, in conjunction with the software tool, was employed to assess the environmental impact. Impact 2022+ method was utilized for characterizing mid-point and end-point impacts.

3. Result and discussion

3.1. Compressive strength

The specimens were cast with formulated mix proportions. Three cubes were tested for each mix and the average value obtained from the testing of the cubes was taken as the final compressive strength value for the mix. From the investigation carried out with the incorporation of calcined granite powder, it was found that the mix with 30 % replacement has shown a significant increase in the compressive strength value when compared to the conventional mix by about 7 %. The compressive strength values for each of the mix in presented in **Figure 6**. The calcined granite powder whicb was added as a partial replacement to the cement makes the matrix of the cement composite dense deceaing the porous medium of the structure. This results in the enhancement of strength (Amin *et al.* 2017).

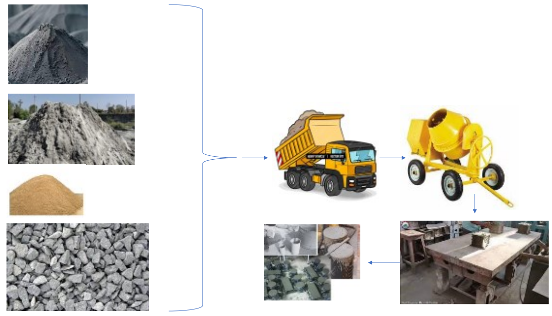


Figure 4. Flow diagram for production of blended cement composites

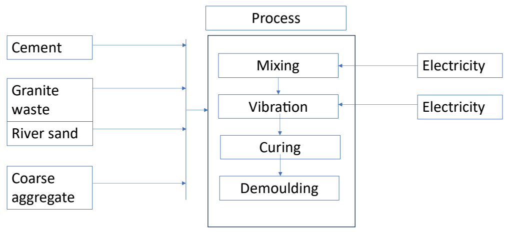


Figure 5. System boundary for synthesis of belnded concrete

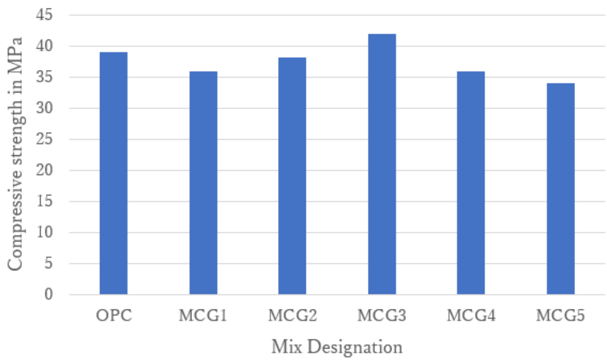


Figure 6. Compressive strength of concrete

3.2. Split tensile strength

The specimens were cast with formulated mix proportions. Three cylinders were tested for each mix and the average value obtained from the testing of the cylinders was taken as the final split tensile strength value for the mix. The split tensile strength for each of the mix reported is shown in **Figure 7**. From the investigation carried out with the incorporation of calcined granite powder, it was found that the mix with 30 % replacement has shown a significant increase in the split tensile strength value when compared to the conventional mix by about 11 %. The granite powder which was added acts as filler in the beginning, thereby crates nucleation sites after which participates in the hydration process making the matrix dense structure. This phenomenon enhances the strength of the concrete sybthesised from the calcined granite powder (Praseeda and Rao., 2021).

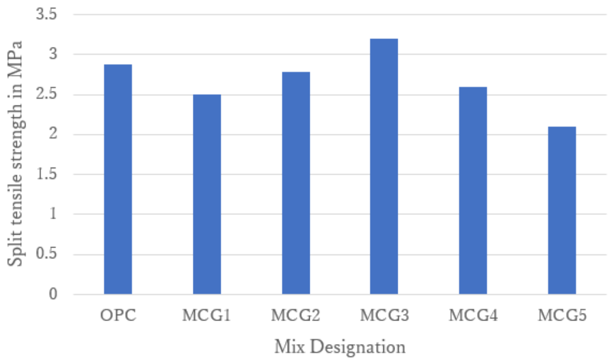


Figure 7. Split tensile strength of concrete

3.3. Flexural strength

The specimens were cast with formulated mix proportions. The flexural strength of each of the mix is presented in **Figure 8**. Three prisms were tested for each mix and the average value obtained from the testing of the prisms was taken as the final flexural strength value for the mix. From the investigation carried out with the incorporation of calcined granite powder, it was found that the mix with 30 % replacement has shown a significant increase in the flexural strength value when compared to the conventional mix by about 13 %. The refinement of the matrix with the addition calcined granite powder with the formation of additional C-S-H might be the reason for the enhancement of the strength (Li *et al.* 2013).

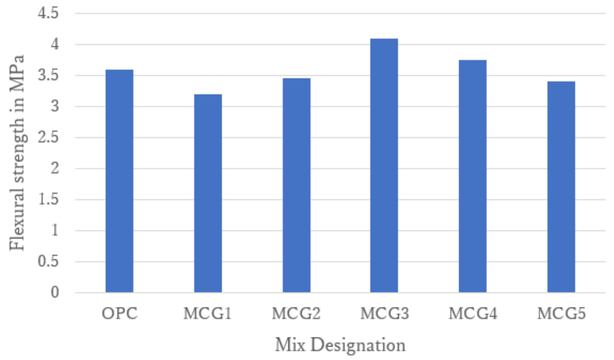


Figure 8. Flexural strenth of concrete

3.4. LCA impact assessment

3.4.1. Midpoint environment impacts of formulated mix proportions

Figure 9 illustrates the environmental impact associated with the production of 1 m3 of concrete using calcined granite powder as partial replacement and their formulated mix proportions. A comparative life cycle assessment (LCA) was conducted, contrasting the environmental impacts of concrete with calcined granite powder as partial replacement for cement. The results revealed a positive environmental impact associated with the incorporation of calcined granite powder. Upon evaluating the environmental impact across different concrete mixes (MCG1 to MCG5), all variants demonstrated reduced impact on climate change compared to control mix (OPC).

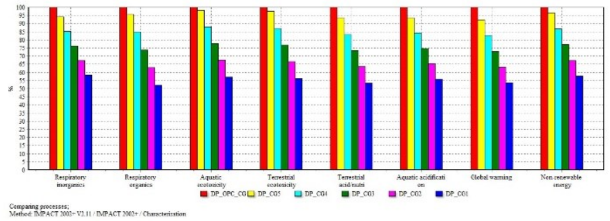


Figure 9. Mid-point characterization impacts for 1 m^3 of concrete

3.4.2. Endpoint environmental impact of studied bricks

The life cycle analysis, focusing on endpoint categories, is depicted in **Figure 10**. Examining the endpoint environmental impact concerning human health, ecosystems, climate change and resources, CG1 demonstrates a positive impact on the environment compared to all the variation and control mix. The analysis suggests that MCG1 not only fulfils the functional requirements but also exhibits sustainable features. Consequently, it can be aptly labelled as optimized proportion for replacement, given its minimal contribution to environmental impact compared to control mix.

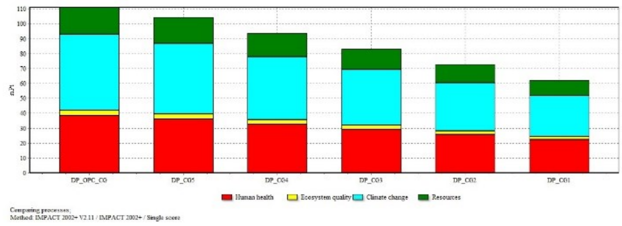


Figure 10. End-point characterization impacts for 1 m3 of concrete

4. Conclusions

The incorporation of different proportions of calcined granite powder a partial replacement to cement showed a significant improvement in the strengths of the concrete. Concrete with replacement level of 30 % has shown the highest value of strengths of about 7 % increase in the compressive strength was observed at 30 % replacement, about 11 % increment in the flexural strength and about 13 % increase in the split tensile strength was observed.

From the results obtained optimum content of the replacement was found to be 30 %. Upon evaluating the environmental impact across different concrete mixes (MCG1 to MCG5), all variants demonstrated reduced impact on climate change compared to control mix (OPC). MCG3 demonstrates a positive impact on the environment compared to all the variation and control mix. The analysis suggests that MCG3 not only fulfils the functional requirements but also exhibits sustainable features.

Authors contribution

DP: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft., Project administration

RRG : Conceptualization, Methodology, Investigation

VRSC: Conceptualization, Methodology, Investigation, Writing -review & editing,

Data availability

Not applicable

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Declarations

Ethics approval: Not applicable.

Consent to participate: Not applicable.

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Conflict of interest

The authors declare no competing interests.

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