Waste Coal Cement Concrete for Sustainable Production

Sevket Can Bostanci[a], Ede Isaac Ajogi[a], Hsein Kew[b]

[a] Assisstant Professor, Dept. of Civil Engineering, European University of Lefke, Lefke, Northern Cyprus, TR-10 Mersin, Turkey (sbostanci@eul.edu.tr), ORCiD: 0000-0002-1493-6147.

[a] MSc student, Dept. of Civil Engineering, European University of Lefke, Lefke, Northern Cyprus, TR-10 Mersin, Turkey (edeisaac12@gmail.com)

[b] Associate Professor, Dept. of Civil Engineering, Surveying and Construction Management, Kingston University, London, United Kingdom (h.kew@kingston.ac.uk)

CORRESPONDENCE Assisstant Professor, Dept. of Civil Engineering, European University of Lefke, Lefke, Northern Cyprus, TR-10 Mersin, Turkey (sbostanci@eul.edu.tr)

Abstract

Concrete industry aims to mitigate its environmental footprint and provide cost-effective approaches for the promotion of sustainable development goals. Waste utilisation in concrete production could satisfy sustainability credentials. However, performance of waste incorporated mixes is not fully clear which limits the use of waste materials. Thus, a clear quantitative evaluation cannot be established. Locally obtained waste coal ash (WCA) was used in this study as a replacement to both CEM I and CEM II/B-S cements with replacement levels of 10% and 20% to achieve sustainable concrete production. Developed concretes were tested against various engineering properties (slump, density, compressive strength, water permeability and porosity) and sustainability characteristics (social, environmental and economic). A balanced scoring system have been used to evaluate the overall performance of laboratory mixes.

Results revealed that WCA use provided similar slump values but reduced the fresh density. WCA mixes had lower compressive strength but enhanced absorption characteristics. Environmental and economic sustainability showed significant reductions while social sustainability indicators (sound permeability and thermal conductivity) showed enhanced performances for WCA mixes suggesting potential use for sustainable construction applications. Overall performances suggest that WCA mixes can improve overall performance by 11% and 15.5% for 10% and 20% replacement levels respectively.

Keywords: Sustainable concrete; sustainable development; coal ash; thermal conductivity; waste; composite cement

1. Introduction

Concrete industry contributes to the global warming through greenhouse gas emissions during the production whereas, CO_2 emissions are the major contributor. It is revealed that the cement production is responsible from 8% of the global CO_2 emissions (Andrew, 2018). Most (90%) of concrete CO_2 emissions are associated with the Portland cement (PC) production. Worldwide cement manufacturing was around 4.1 billion tonnes in 2018 (de Brito & Kurda, 2021). However, agreement to bring down global CO_2 emissions to decline the effect of global warming was addressed under both the Kyoto Protocol and Paris Agreement (United Nations, 2015). Low carbon cement-based waste materials have been mostly introduced in concrete production to replace PC aiming to lower CO_2 emissions and materials sent to landfill. Total waste generation is estimated as 2.1 billion tonnes annually (Kaza et al., 2018). It is assumed that global coal fly ash has approached to 780 million tons (Koshy et al., 2019). Waste coal ash (WCA) is one of the waste materials in Cyprus, which is disposed through landfilling. Landfilling of waste materials may reduce the available virgin territories and could potentially jeopardize the sustainable living for the future generations, thus managing waste is of a great concern (Haibin & Zhenling, 2010). Furthermore, landfilling of WCA may lead to contamination of the groundwater through leaching of heavy metals or hazardous materials (Alderete et al, 2021). Singh (Singh et al, 2018) reported that WCA could increase the skin, lung and bladder cancers but also effect red blood cells in humans. Concrete production is one of the best options to reclaim those materials and reduce the environmental burden (Ding et al, 2016). Various studies have studied the effects of various waste materials (Aydin, 2016; Flegar et al, 2020; Mosaberpanah et al., 2019; Shishkin et al., 2021; Siddique, 2012; Ulubeyli et al, 2017; Yüksel et al, 2017).

A study by Li and Wang (2019) reported that WCA is becoming one of the typical solid waste around the globe. Various studies have been performed on the use of WCA as both cement replacement (Bajare et al., 2013; Canpolat et al., 2004; Hwang & Cortes, 2021; Opiso et al., 2019, Oruji et al., 2017) or aggregate replacement (Hannan et al., 2020; Jang et al., 2016; Kim et al., 2012; Kumar & Singh, 2020; Muthusamy et al., 2020; Shanmugan et al., 2020; Singh et al., 2018) in concrete production. There is no clear trend regarding to the effect of WCA on fresh concrete properties. Some studies (Gooi et al., 2020; Muthusamy et al., 2020) reported that WCA use reduced workability due to angular texture of WCA increased friction. On the contrary, improvements in fresh properties were also noted (Hwang & Cortes, 2021; Khongpermgoson et al., 2020; Kim et al., 2012; Oruji et al., 2017). Kim et al. (2012) found improvement in slump even though WCA led to increased friction. Singh et al. (2018) stated that rougher surface of WCA increased water demand. A study by Nakamura et al. (2021) revealed that water content is physical and chemical characteristics of WCA concrete. WCA use was observed to reduce the concrete density due to lower specific gravity of WCA (Hannan et al., 2020; Kim et al., 2012; Singh et al, 2018; Ting et al, 2020). In general, existing studies (Bajare et al., 2013; Demirboga, 2007; Hannan et al., 2020; Jang et al., 2016; Kim et al., 2012; Muthusamy et al., 2021a; Ting et al.,

2020) suggested that WCA addition reduced the concrete strength. Kim (2012) and Muthusamy et al. (2021b) claimed that reduction in strength is due to increased porosity through WCA addition. Another study (Opiso et al., 2019) reported slow strength development. Similar finding was also reported by Jang et al. (2016) whereas strength loss was minimized at 28d compared to 3d. Some studies (Kurama & Kaya, 2008; Singh et al., 2018) found optimum WCA content of 10% for the enhanced strength property while over 10% WCA were observed to reduce strength. Gooi et al. (2020) reported various trends for compressive strength and claimed that variability is due to the chemical additive content used. On the contrary, Oruji et al. (2017) reported higher strength due to ultrafine chacteristics of WCA. Muthusamy et al. (2020) stated that WCA could contribute to strength through pozzolanic reactions at longer ages. Previous studies (Arun et al., 2020; Khongpermgoson et al., 2020) also noted that increasing fineness of WCA could increase the pozzolanic activity. Permeability properties of WCA incorporated mixes were observed to be adversely effected (Muthusamy et al., 2020; Opiso et al., 2019). Previous studies (Kim et al., 2012; Kumar & Singh, 2020; Oruji et al., 2017) reported higher porosity when WCA is present. Some studies (Gooi et al., 2020; Singh et al., 2018; Ting et al., 2020) revealed that water absorption increased as the WCA increased which is claimed to be due to voids induced by WCA. In contrast with WCA, GGBS utilization was found to reduce concrete permeability (Jindal et al., 2020; Mostofinejad et al., 2021).

Most of the studies pointed out the potential influence from general perspective when sustainability is concerned. Hossain et al. (2021) emphasized the importance of producing durable and sustainable concrete whereas Jang et al. (2016) stated that durability is important factor when social cost in considered. In addition, Zuo et al. (2012) studied the social sustainability in construction and revealed the importance of sustainable management. According to Zuo et al. (2012), corporate social responsibility is the key to successfully implement social and environmental sustainability in business operations. Scope et al. (2021) stated that sustainable practices require interdisciplinary coordination of engineers, economists and environmental scientists for a common understanding. Huising et al. (2015) suggested that carbon reduction strategies to satisfy sustainable development should start from the smallest scale, as possible, which will then affect the global scale. Most of the existing studies (Arun et al., 2020; Gooi et al., 2020; Hwang & Cortes, 2021; Singh et al., 2018) claimed that WCA could provide environmentally-effective solution and reduce environmental burden. According to Bajare et al. (2013), WCA should be further grinded to be used as a cement replacement and this could require more energy which will increase associated eCO_2 emissions and cost. Another study by Purnell and Black (2012) reported cement as being the main contributor to the concrete eCO_2 emissions. Martinez-Lage et al. (2020) claimed that waste materials reduce compressive strength and thus, higher cement content is required for the same strength which may effect environmental and economic assessments. The Concrete Centre (2018) identified 81 kg CO_2/ton for a standardised mix, 89% was associated with production while 11% due to transportation. Another study (Hammond & Jones, 2011) found 132 kg eCO_2/t and 151 kg eCO_2/t for 32/40 MPa and 40/50 MPa strength classes of concretes.

In addition, Hwang and Cortes (2021) expressed that locally available waste materials could be beneficial from social and economic sustainability perspectives. Bajare et al. (2013) revealed that economic benefits should be reasonable in order to use waste materials. A report by the Concrete Centre (2020) reported that recycled aggregate materials should be brought from 15 km radius. There is no clear information on the range of waste materials as a cement replacement and this range varies with the type of waste material used. There are limited information on the other social sustainability related concrete properties. Plati (2019) revealed that social sustainability is remarkably important which could display negative impact on people if it is perished. Hajek (2017) stated concrete could conduce to social sustainability through its effective thermal mass and acoustic properties. Gooi et al. (2020) and Muthusamy et al. (2020) reported lower thermal conductivity at 28d for WCA added concretes due to rise in porosity and reduction in density respectively. Hannan et al. (2020) claimed that WCA can be used as a sound absorber. However, a study by Oancea et al. (2018) revealed that density and porosity are the factors determining sound absorption (at 28d) which needs to be further investigated.

Most of the existing studies focus on the engineering properties of WCA incorporated concretes. However, there is no clear value provided by the existing studies regarding to eCO_2 emissions and cost of WCA mixes associated with social sustainability. The target of this research was to examine the engineering properties and sustainability performances of concretes made with WCA with replacement ratios of 10% and 20% to either cement (CEM I) or Portland-composite (CEM II/B-S) cements. The target 28d design strength for developed mixes was 45 MPa. Developed mixes were tested for several engineering properties (slump, fresh and hardened density, compressive cube strength, water absorption) and sustainability analysis (environmental, economic and social).

2. Materials and Experimental Procedures

2.1. Materials

2.1.1. Cementitious materials

Three cementitious materials were used in this study. Control mix was produced only using PC. Portland composite cement (PCC) (CEM II/B-S) was used with WCA with proportions of 90%PCC+10%WCA and 80%PCC+20%WCA. Chemical compositions of cementitious materials are provided in Table 1.

PC (CEM I)

Cement was used conforming to TS EN 197-1. Specific gravity of cement was 3.15 and had a Blaine fineness of 3407 cm^2/g obtained from the supplier.

PCC (CEM II/B-S)

PCC, 42,5N, was also used in this study by blending 65% PC and 35% Ground granulated blast-furnace slag (GGBS). GGBS was conforming with TS EN 15167-1. Specific gravity of PCC was 3.05 and had a Blaine fineness of 3788 cm^2/g obtained from the supplier.

Waste Coal ash (WCA)

WCA was obtained from a single source for the consistency of the study. Burned coal waste was collected and sieved in the laboratory environment. The 425 μm sieve was used for sieving throughout the research to make sure uniformity of WCA particles and to ensure that coarser particles were removed.

Table 1. Chemical composition of cementitious materials used

Compound	PC (%)	PCC (%)	WCA (%)
CaO	65.1	57.4	8.4
Al_2O_3	5.3	5.9	20.2
SiO_2	20	29.8	50.1
Fe_2O_3	3.7	2.5	9.7
MgO	1.5	3.5	1.3
SO_3	2.4	2.6	1.2
Loss on ignition	3.9	3.3	3.8

2.1.2. Aggregates

Natural sand and gravel with 5.6 mm and 22.4 mm as nominal sizes, respectively, in accord with TS 706 EN 12620+A1. Physical properties of the aggregates used are given in Table 2 and Figure 1. Aggregates used comply with the requirements of the relevant standards.

Table 2. Physical properties of aggregates constituents

Property	Aggregates	
Physical (TS EN 1097, part 6)	**Fine**	**Coarse**
Unit weight (kg/m^3)	1.64	1.50
Apparent density (kg/m^3)	2.85	2.61
Percentage of voids (%)	42.2	42.1
Water absorption capacity (%)	0.84	1.40
Specific gravity	2.84	2.59
Fineness modulus	2.92	4.34

2.1.3. Admixtures

Master Glenium 126, high-range water reducing agent (HRWA) was used conforming with EN 934-2.

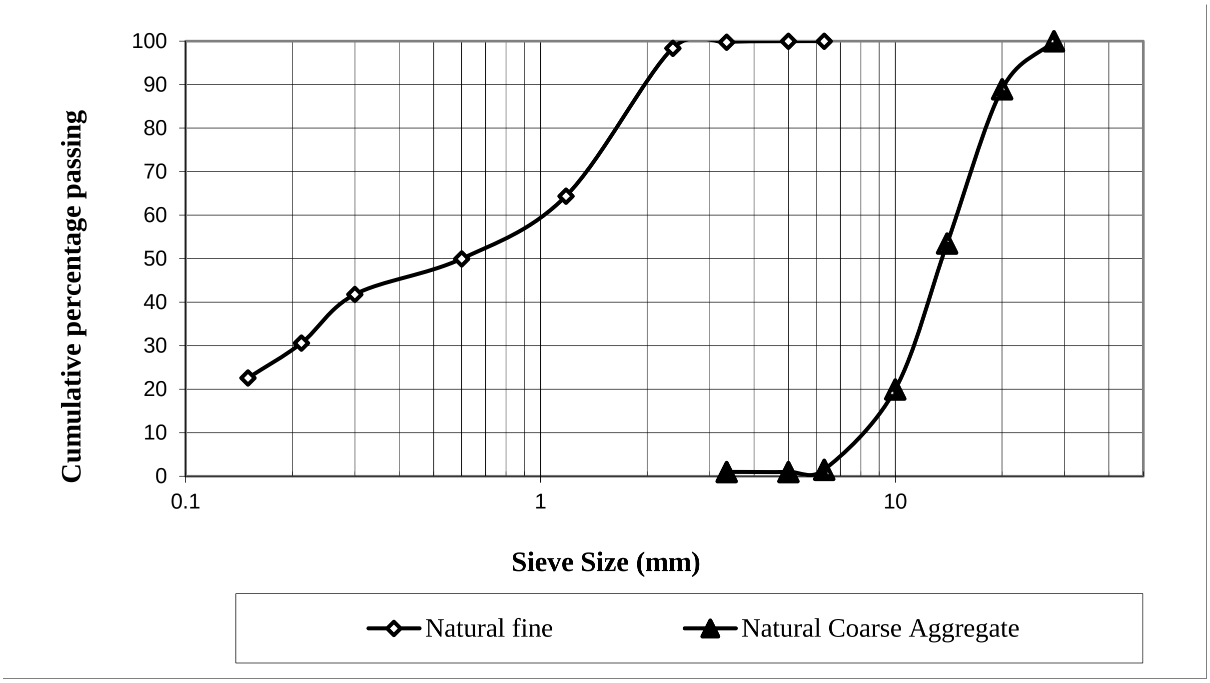

Figure 1. Grading of fine and coarse aggregates

Figure 1. Graphical demonstration of the particle size distribution of fine and coarse aggregates by cumulative percentage passing. Distributions are given in percentile notations against the sieve sizes.

2.2. Mix Design

Mix proportions were established through using Building Research Establishment mix design method. Control mix was established through trial and error based on the 28d target design strength of 45 MPa. The water/binder ratio was determined as 0.45. The mix design was carried out based on density of gravel which led to determination of concrete density, which was 2325 kg/m^3. The percentage of fine aggregates passing 600 µm, obtained through particle size distribution, was used to designate the sand content in the mix. Superplasticizer (SP) was proportioned for control mix to achieve consistency of S3 class (100 to 150 mm) conforming to TS EN 206:2013+A1. After the determination of constituents, PC was replaced by WCA with proportions of 10% and 20% on a mass base and mixes were denoted as 90C-10WCA and 80C-20WCA respectively. For PCC incorporated mixes, pre-blended PCC, with proportions of 65% cement and 35% GGBS, was used instead of CEM I. These mixes were denoted as 90PCC–10WCA and 80PCC–20WCA. WCA contents were established based on primary optimisation mix designs which also aimed to provide lower environmal impact through lowering PC content. Aggregates content were kept the same for all developed mixes. SP content was arranged according to the total binder content. Mix design proportions for all mixes are given in Table 3.

Table 3. Concrete mix designs

Mixes	Constituents proportions (kg/m^3)						
	Water	Cementitious constituents			Aggregates		HRWA
		PC	PCC	WCA	Fine	Coarse	
100PC	220	490	-	-	825	790	4.90
90PC-10WCA	220	440	-	50	825	790	4.90
80PC-20WCA	220	390		100	825	790	4.90
90PCC–10WCA	220	-	440	50	825	790	4.90
80PCC–20WCA	220	-	390	100	825	790	4.90

2.3. Test Procedures

Concrete castings were carried out conforming to TS EN 12350. Mixes were covered with plastic sheet for 24 hours until demoulding. Samples were then taken from the moulds and cured at 20°C until testing in conformity with the requirements of TS EN 12390-2. Table 4 gives test ages of the samples for each test. For each testing, three samples were used and averaged.

Table 4. Test ages for the performed tests

Property	Test	Test ages (days)
Engineering	Hardened unit weight	1
	Compressive strength, MPa	1, 7, 14, 28 and 56
	Water Permeability, (%)	28

Sustainability	Thermal Conductivity, (λ (W/mK))	28
	Sound Permeability, (%)	28

2.4. Engineering Properties

2.4.1. Compressive Cube Strength

Compressive strength results were established through 150 mm cubes. Cubes were tested at 1d and 7d for the early age strength determination and at 28d and 56d to monitor whether target design strength was achieved and presence of potential pozzolanic activity respectively.

2.4.2. Water Permeability

Permeability property is one of the factors in the determination of concrete durability. Concretes with lower permeable pore capacity could resist better against penetration of hazardous chemical and increases service life. The water permeability test was conducted in accordance with TS EN 12390-8 at 28d. 150mm cubes samples were used to identify water permeability property of laboratory mixes. Cube samples were cured under the water until the test age and oven-dried for 24 hours to ensure moisture is removed. Test samples were positioned on the test equipment which water was applied with a pressure of 5±0.5 bars with a precision of 0.2 bars. Water pressure was applied, through a 75 mm diameter from the bottom of the test sample, for the 72 hours. First and last water levels on the scale was recorded and permeability property was established in percentages.

2.5. Sustainability Performance

2.5.1. Environmental Sustainability

Traditional approach adopted in Cyprus suggests the use of cement for the concrete production. However, cement is mostly known for its contribution to concrete eCO_2 emissions. Thus, use of waste materials replacing energy-intensive cement will undoubtedly lower the eCO_2 emissions (Shi et al., 2019; Yilmaz et al, 2016. The eCO_2 emissions associated with concrete production was calculated which is based on materials delivery to the casting site, the European University of Lefke. Emission calculations include importation of cement from Turkey, processing of raw materials for cement production, delivery to the port, sea shipping from Turkey to Cyprus, delivery from port to silo, conveying to silo for storage and discharging from the silo to production site. Emission associated with aggregates include extraction and processing of raw materials and delivery to the concrete plant. Table 5 and Table 6 give the materials and associated transportation distances for concrete production and energy and emissions for materials and processes used for concrete production respectively. The environmental emissions data were obtained in collaboration with a local ready-mixed concrete company limited and its sub-company where the natural aggregates were supplied from. CEM II/B-S cement was obtained as blended from the same supplier, and thus, emissions associated with transportation is assumed to be the same as cement. Distances were considered from the constituents delivery to the construction site as the European University of Lefke. Fig. 2 gives the schematic demonstration of the concrete production system boundaries.

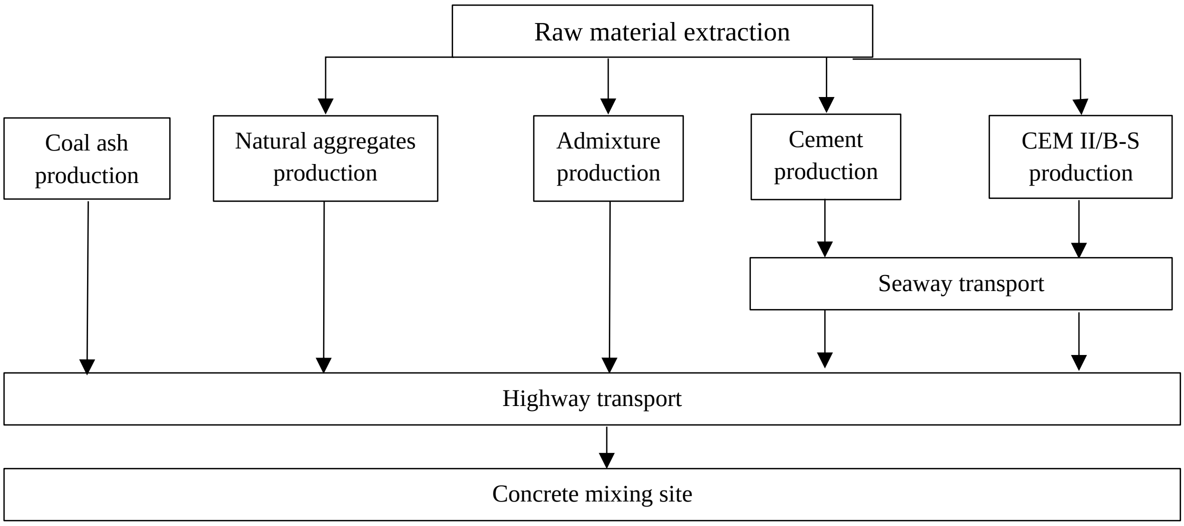

Figure 2. System boundaries for the concrete production

Figure 2. Arrow diagram shows summary of the processes included in the calculation of environmental sustainability

Table 5. Materials and associated transportation distances for concrete production

Materials	**Source location**	**Distance (km)**	**Transportation type**
Cement	Seaway shipping to port	75	-
	Total highway transport to production site	116.5	By 30t truck
WCA	Highway transport to production site	57.3	By light-duty vehicle
Aggregates	Total highway transport to production site	72.5	By 30t truck
Admixture	Highway transport to production site	64.4	By light-duty vehicle

*Source of data is obtained through survey with the suppliers (Bostanci, 2020)

Table 6. Energy and emissions for materials and processes used for concrete production

Materials	Process	Embodied energy (MJ/kg)	Embodied CO_2 emissions kg CO_2/kg	Sources of data
Cement	Cement production	4.50	0.71	(Hammond & Jones, 2011)
	Seaway transportation	0.0162	0.000525	(International Maritime Organization, 2014)
	Cement loading at port	0.00088	0.00015	Survey with supplier
	Cement discharge at port	0.00088	0.00015	Survey with supplier
	Transport to silo	0.00088	0.00015	Survey with supplier
	Cement loading at silo	0.00088	0.00015	Survey with supplier
	Loading cement from silo	0.00088	0.00015	Survey with supplier
	Transport to production site	0.35	0.03728	(International Maritime Organization, 2014; Rossit & Lawson, 2012)
GGBS	GGBS production		0.0796	(The Concrete Centre, 2020)
WCA	Transport to production site	-	*	(EPRS, 2018)
	Processing (sieving)		**	Based on national tariffs
Aggregates	Extraction and processing	0.1	0.005	(Hammond & Jones, 2011)
	Transport to production site	0.0702	0.0232	Survey with supplier
Admixture	Admixture production	0.0058	0.0022	Survey with supplier
	Transport to production site	-	***	(EPRS, 2018)

* represents transportation emissions of WCA, calculated as 9.36 kg CO_2 per trip,**represents emissions for coal ash use due to electricity generation are 0.164 kg CO_2 per 1 hour of sieving. ***represents transportation emissions of admixture, calculated as 10.5 kg CO_2 per trip

2.5.2. Economic Sustainability

Economic sustainability is mostly considered for the feasible application of waste materials. Economic feasibility has always been an important factor for concrete production. According to Santos et al. (2015), economic sustainability is given more priority than environmental and social sustainability. An earlier study (Martinez-Lage et al., 2020) claimed that transportation is one of the factors of economic sustainability. Similar statement was pointed out by Abbasi and Nilsson (2016) reporting sustainable transportation is linking the environmental and economic sustainability facets. Federal Highway

Administration (2016) specifies material stage including raw materials extraction and manufacturing, transportation to the plant, mix design and proportioning and from the plant to the construction site. Material delivery distances are given in Table 6. Material costs are based on the national tariffs for production and transportation phases.

2.5.2. Social Sustainability

Thermal Conductivity

Occupant require higher quality of living in their residents for their health and well-being (Barbulescu & Lafargue, 2016). As the quality of the life for the occupants has been one of the major focus points under the sustainable construction tools (Mishra, 2020), construction materials with better inherent thermal conductivity property has drawn interest. Building fabric with lower thermal conductivity could decrease the energy demand for heating and cooling and provide better comfort from health and well-being perspective (Leo Samuel et al., 2017). The thermal conductivity test was conducted through steady state principle guarded hot plate test equipment in this study. Test was conducted according to TS EN ISO 10456 and ISO 8302. Test samples were water-cured until the test age and then removed and air-cured for 24 hours before testing. The heat was applied through the lower part of the equipment that was set to 40°C whilst upper part was set to 20°C to maintain temperature difference ($\Delta T = 20°C$) for all mixes. Samples were surrounded with polystyrene foam to prevent heat loss and gain from the surrounding environment.

Sound Permeability

World Building Council (2020) stated that one of the recent challenges in the sector is to provide acoustically effective construction to enhance life quality by keeping the indoor ambient noise levels at pleasing levels. For sound permeability testing, concrete samples were placed to the test location and covered with polystyrene foam to prevent any interfering sounds from the environment for consistency. The same continuous sound was applied through a speaker mounted at the bottom of the test mechanism for a duration of 1h and sound permeability value was calculated in percentage based on given and received sound values in decibels.

Social sustainability of developed mixes was measured through sound permeability and thermal conductivity properties of developed mixes. Properties were determined through 500 mm x 500 mm square samples with thickness of 40 mm. Samples were water cured until the test age of 28d. Samples were then taken out of the water and air-cured in the room temperature for 24h prior to testing.

2.6. Balanced Score Model

Sustainability is an interconnected concept which includes environmental, economic and social facets. Environmental and economic sustainability is mostly paid attention due to concerns on the built environment and feasible application respectively while social sustainability is mostly not considered. Hafez et al. (2021) pointed out the challenge for sustainability performance calculations and expressed that it is not easy for occupants to study the optimum mix based on combined, functional, environmental and economic influences. Zuo et al. (2012) stated that corporate social responsibility is an important ideology from the social and environmental aspects. Successful application of corporate social responsibility at all levels in a company could provide social and economic benefits. Earlier study by Petrini and Pozzebon (2009) revealed a score card model as a good approach to integrate social and environmental facets with internal processes. According to Kaplan and Norton (1991), score card model includes financial, customer, internal business and innovation and learning perspectives. Internal business perspective will be considered for this study. For this aim, performances of all developed mixes will be rated in comparison to control mix. Engineering performances and sustainability assessments will be considered for this model.

3. Results and Discussion

3.1. Engineering Properties

3.1.1. Slump Test

Workability property of developed mixes was established through slump test. All concrete mixes, achieved target consistency class of S3 (100-150mm) with relevance to TS EN 206-1. Obtained results are revealed in Fig. 3. It is worth mentioning that SP content was remained the same for all mixes and thus, results can be directly linked with WCA and CEM II/B-S materials characteristics. Slump values were decreased for WCA incorporated mixes except 90CEM II/B-S-10WCA mix. Reductions were reported as 6.3% and 12.5% for 90C-10WCA and 80C-20WCA mixes respectively than the control mix. 90CEM II/B-S-10WCA mix had a higher slump of 6.3% while; 80CEM II/B-S-20WCA mix had a lower slump by 3.1% compared to the control mix. General trend observed was that slump values were lowered as the WCA content increased in both, CEM I and CEM II/B-S mixes. Specific surface area is expected to reduce as WCA has coarser particles compared to C and CEM II/B-S cement mixes and thereby less water is needed to coat the surface of particles. Slump reduction in WCA incorporated mixes might be initially linked with the increased water demand through hygroscopic nature and porous characteristics of WCA (Hasim et al., 2022; Singh et.al, 2022). Furthermore, slump reduction of WCA mixes may also be linked with sharp-edged and irregular texture led to rougher surface and increased friction (Singh et al., 2022; Gooi et al., 2020; Kim et al., 2012). Thus, it has led to the reduced dispersion of concrete constituents and increased water demand to achieve the same consistency. Higher slump values of CEM II/B-S mixes compared to counterpart 90C-10WCA and 80C-20WCA mixes could be due to less water requirement of GGBS particles for the same consistency (Khan et.al, 2014). Reduced water demand is believed to be due to smooth surface texture led to better dispersion of constituents for CEM II/B-S mixes (Bostanci et al., 2016a; Megat Johari et al., 2011; Khan et.al, 2014).

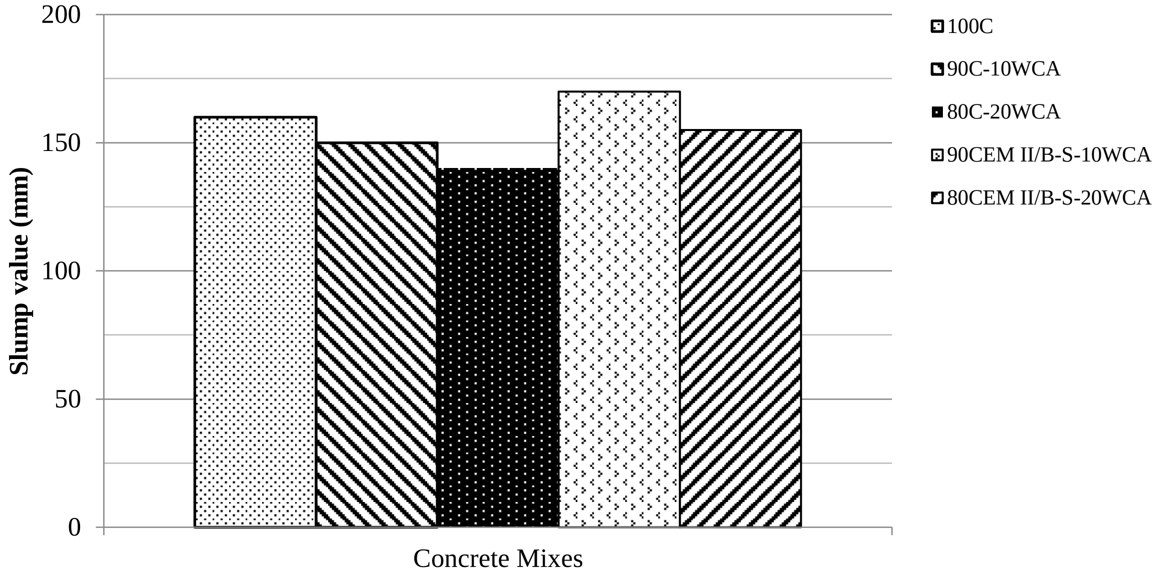

Figure 3. Slump test results

Figure 3. Bar chart shows the slump values of the laboratory mixes to monitor the effect of WCA use in C and CEM II/B-S cement concretes. Varying patterns were used for bar charts to represent 100C, 90C-10WCA, 80C-20WCA, 90CEM II/B-S-10WCA and 80CEM II/B-S-20WCA from left to right hand sight respectively. These patterns were used for the whole bar chart demonstrations throughout the manuscript.

3.1.2. Fresh and Hardened Unit Weight

Fresh and hardened unit weight results are revealed in Table 7. Amongst developed mixes, 100C cement mix reported the highest fresh density compared to WCA utilized mixes. Fresh unit weights were observed to reduce as WCA content increased in both C and CEM II/B-S cement mixes. Reductions were reported as 3.7% and 4.9% for 90C-10WCA and 80C-20WCA cement mixes respectively, while, fresh unit weights were decreased by 3.6% and 4.2% for 90CEM II/B-S-10WCA and 80CEM II/B-S-

20WCA cement mixes. It is important to mention that total aggregate proportion was maintained the same for all mixes. Thereby, the reduction in fresh density could be directly linked with the lower specific gravity of cementitious materials used, WCA and GGBS.

Similar trend as fresh unit weight was observed for hardened unit weight property. Mixes were designed to have hardened unit weight of 2325 kg/m^3. Control mix unit had the highest unit weight of all mixes. Binary and ternary cement mixes had lower unit weight compared to control mix. Reductions were noted as 4.2% and 4% for 90C-10WCA and 80C-20WCA cement mixes, whilst 90 CEM II/B-S – 10WCA and 80 CEM II/B-S – 20WCA cement mixes had 3.8% and 4% reductions. As mentioned previously, lower unit weight values are associated with the lower unit weight of the WCA and GGBS compared to C. This is consistent with the earlier studies (Hannan, et al., 2020; Kim et.al, 2012; Singh et.al, 2018). The change between fresh and hardened properties can be also seen from Table 7. Control mix showed 1.3% reduction between fresh and hardened densities. However, weight losses were reported as 0.9%, 0.4%, 1.5% and 1.1% for 90C-10WCA, 80C-20WCA, 90 CEM II/B-S – 10WCA and 80 CEM II/B-S–20WCA cement mixes respectively. Weight losses were decreased for 80C-20WCA and 80 CEM II/B-S–20WCA cement mixes compared to 90C–10WCA and 90 CEM II/B-S–10WCA cement mixes. Cement hydration consumes water which is influenced by silica and alumina. Weight loss reductions might be associated with reduced hydration rate due to increased porosity. This is believed to trap free water content which did not contribute to hydration and led to decreased weight loss between fresh and hardened density.

Table 7. Fresh and hardened density test results

Mix	Fresh Density (kg/m^3)	Hardened Density (kg/m^3)
100C	2355.0	2324.7
90C-10WCA	2268.6	2249.1
80C-20WCA	2240.6	2231.3
90 CEM II/B-S-10 WCA	2270.1	2235.5
80 CEM II/B-S-20 WCA	2256.8	2232.0

3.1.3. Compressive Cube Strength

Compressive strength results are given in Fig. 4. Standard deviations were noted as 1.3 MPa, 1.2 MPa, 1.5 MPa, 1.6 MPa and 1.6 MPa for 100C, 90C-10WCA, 80C-20WCA, 90 CEM II/B-S-10WCA and 80 CEM II/B-S-20WCA cement mixes respectively. The 28d results showed that only control mix achieved the target design strength of 45 MPa. In general, all mixes achieved lower compressive cube strengths except 90PC-10WCA cement mix at 56 days compared to control mix. Findings were consistent with Bhat (2021) who reported 10% WCA as the optimum replacement level when compressive strength is concerned. Compressive strength values were decreased as WCA increased. In addition, ternary (PC-GGBS-WCA) cement mixes also reported lower values compared to binary (PC-WCA) cement mixes. For ternary mixes, lower strength developments were reported at all ages. WCA mixes had lower compressive strength results which is consistent with earlier studies (Kim et al., 2012; Mangi et al., 2019; Thi et al., 2021). Strength losses were more prominent at early ages (<7d). Earlier study by Erdem and Kirca (2008) claimed that utilization of mineral admixtures led to lower surface area and thus do not contribute to strength gain at early ages. Strength losses were found as 26.3%, 43.4%, 44.6% and 48% at 1d while 4.3%, 13.4%, 17.7% and 25.1% at 7d for 100C, 90C-10WCA, 80C-20WCA, 90 CEM II/B-S-10WCA and 80 CEM II/B-S-20WCA mixes respectively. Slow strength development was also noted by Opiso et al. (2019). Strength losses were lessened between 1d and 7d. These reductions in early age strength can be linked to both physical and chemical factors. WCA used was sieved through 425 µm and coarser than C. Coarser WCA particles may have reduced the potential influence of pozzolanic reactivity at the initial ages (Arun et al., 2020). Gooi et al. (2020) revealed that WCA should be grinded to be used as a cement replacement. In addition, increased water demand, as noted earlier in the workability section, is believed to lead to the formation of excessive structural pores. Free water content is then trapped in these pores which may have weakened the interfacial transition zone between the constituents and reduced initial hydration for WCA mixes compared to control mix. In addition, reduced compressive strengths of WCA-utilized mixes can be also associated with a lower density of these mixes. For chemical perspective, reduced strength development was due to lower clinker content lowered CaO content, and reduced hydration rate and led to lower strength values. Lower strength losses at 7d compared to 1d is assumed to be due to active silica presence in WCA (Table 2) reacted with the trapped water in the pores and unhydrated $Ca(OH)_2$ promoted formation of C-S-H gel. Strength losses were further decreased at 14d and 28d. An earlier study by Cheng et al. (2022) also found a considerable increase in compressive strength after 7d. Losses were reported as 4.1%, 12.6%, 17.4% and 22.1% at 14d while 4%, 11.3%, 17.2%, and 20.9% at 28d for 100C, 90C-10WCA, 80C-20WCA, 90 CEM II/B-S–10WCA and 80 CEM II/B-S-20WCA mixes respectively supporting pore refinery effect of WCA through the further promotion of C-S-H. Kaur et al. (2019) also reported additional hydration which improved compressive strength. At 56d, 90P-10WCA mix had higher compressive strength (3.1%) compared to control mix whilst 10.5%, 16.8% and 19.9% lower strengths were recorded for 80C-20WCA, 90 CEM II/B-S-10WCA and 80 CEM II/B-S-20WCA mixes respectively. Reduced strength losses over time could be an indication pozzolanic activity through WCA. Cheriaf et al. (1999) found that WCA contributes to pozzolanic reactions at post 28d. WCA chemical composition used in this study could indicate WCA as pozzolanic material since it satisfies ASTM C618 (2019) requirement for pozzolanic presence ($Fe_2O_3 + Al_2O_3 + SiO_2 > 70\%$).

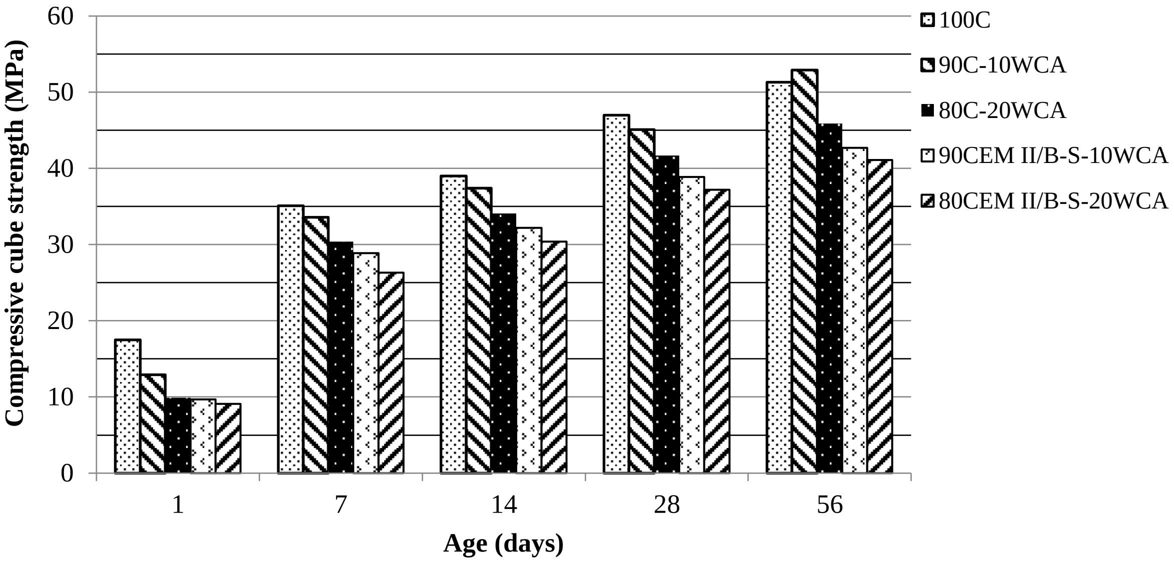

Figure 4. Compressive cube strength results

Figure 4. Bar chart provides early (<7d), target (28d) and long (>28d) term strengths of the concrete mixes that represents the strength developments over time at 1d, 7d, 14d, 28d and 56d. Varying strength developments over time is revealed in the bar chart.

3.1.4. Water Permeability and Porosity

Water permeability and porosity test results are revealed in Fig. 5. Water permeability values ranged between 5.7% and 8.9%. According to Neville (2008), good concretes should have less than 10% of absorption value. Control mix had the highest water permeability. 90C-10WCA and 80C-20WCA cement mixes had lower permeability by 29.2% and 25.8% respectively while 36% and 33.7% reductions were reported for 90CEM II/B-S-10WCA and 80CEM II/B-S-20WCA mixes respectively. Lower water permeability of WCA incorporated mixes was in contrast with previous studies (Muthusamy et al., 2021b; Thi et al., 2021) which claimed higher water permeability due to porous nature of WCA. Porous characteristics of WCA mixes were noted in the slump test. Even though pozzolanic contribution is suggested by compressive strength values, lower water permeability is mainly linked to physical properties. Reductions are believed to be associated with coarser particles of WCA acting as a bridge between cementitious materials and fine aggregates that could reduce inter-connected capillary pores through optimal particle packing of the constituents. Strength development between 1d and 28d also suggested potential pore refinement for WCA mixes between 1d and 28d through a pozzolanic contribution of WCA. As noted earlier in compressive strength section, silica present in WCA is believed to provide extra C-S-H gel by reacting with $Ca(OH)_2$, which then enhanced the pore matrix and reduced permeability. This is more apparent in ternary cement mixes due to increased pozzolanic activity by WCA and GGBS particles (Ban et.al., 2022). Even though binary and ternary mixes had lower water permeability values, water permeability values increased when WCA content increased. This is due to higher water absorption, as suggested by slump test results, which increased permeability by 4.7% and 3.5% compared to counterpart 10-WCA mixes.

Porosity test results followed a similar approach as water permeability. A good correlation (R^2=0.86) was reported between water permeability and porosity results given in Fig. 6. Porosity values ranged between 9.9%-12.9%. Control mix had the highest porosity value. Reductions in porosity values were reported as 23.3%, 22.5%, 21.7% and 19.4% for 90C-10WCA, 80C-20WCA, 90CEM II/B-S–10WCA and 80CEM II/B-S–20WCA mixes respectively. Similar to water permeability, reduction in capillary pores could be linked with optimal particle packing which can be supported by compressive strength values. It is believed that increased structural pores as reported earlier were compensated by both increased particle size of WCA and densified matrix through pozzolanic refinement. Lower porosity may also be associated with filler effect of WCA which is coherent with a previous study (Ban et.al, 2022). The results are also coherent with Kaur et.al. (2019) who claimed lesser voids for coal ash mixes due to additional hydration which covered pore spaces. Permeability and porosity results suggest that laboratory mixes could provisionally provide better resistance against severe exposures through matrix refinement.

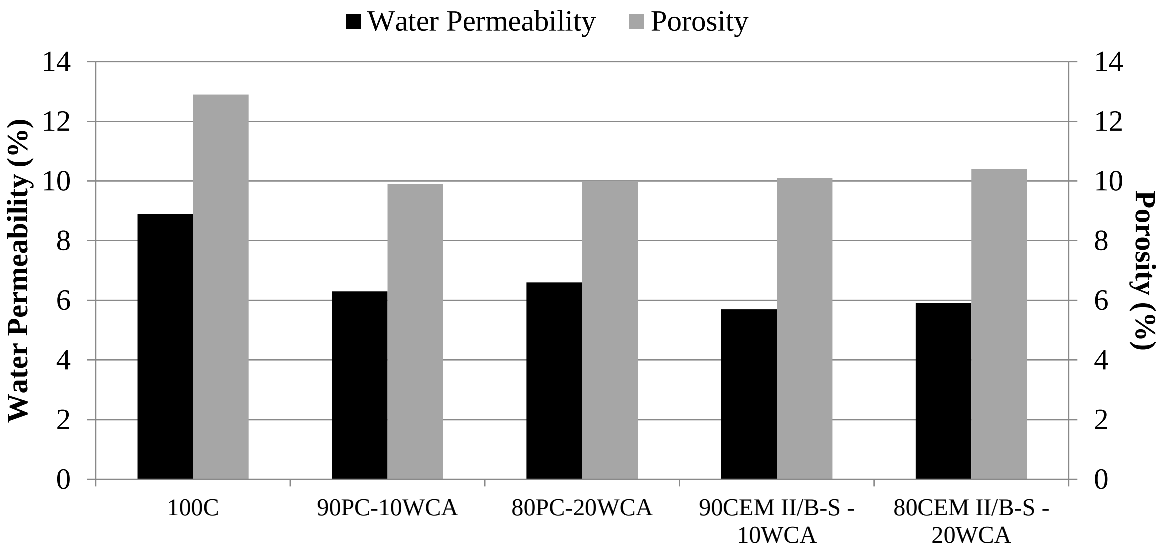

Figure 5. Water permeability and Porosity test results

Figure 5. Pair of histogram bar charts with two y-axes reveals water permeability and porosity values to reveal potential relation between these two permeability related properties. Black bar charts indicate

water permeability values that is represented on the left y-axis and while grey bar charts indicate porosity values that are on the right y-axis for each mix.

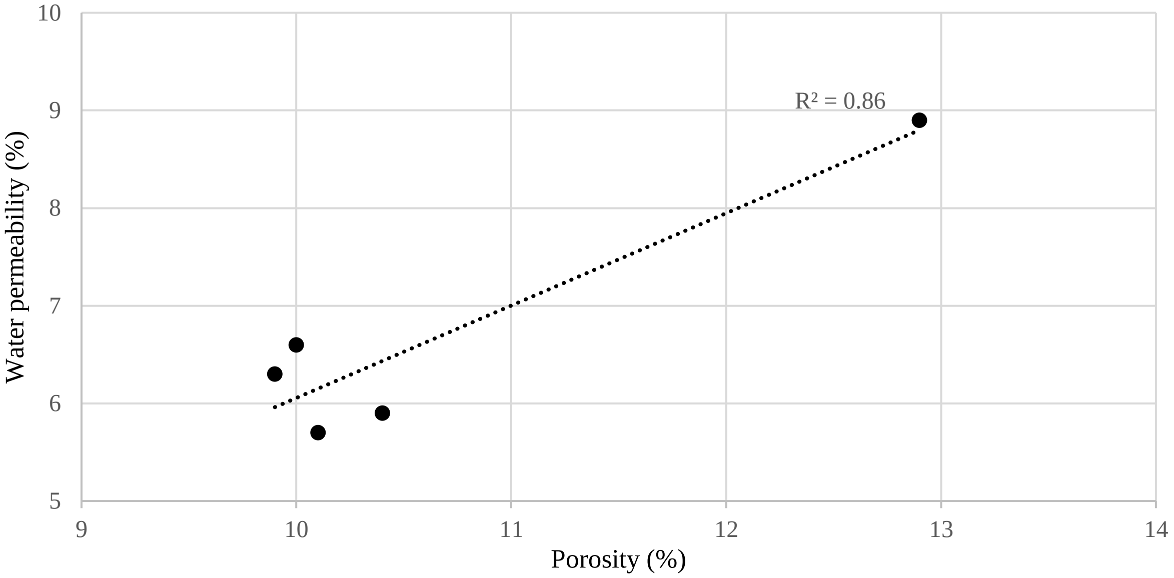

Figure 6. Relationship between water permeability and porosity

Figure 6. Graphical demonstration shows the correlation between water permeability (y-axis) and porosity (x-axis) values. A trend-line was added and correlation value was provided as $R^2 = 0.86$.

3.2. Sustainability Assessment

3.2.1. Environmental Analysis

The eCO_2 emissions of laboratory mixes are presented in Fig. 7. Control mix had the highest eCO_2 emissions (412.1 kg eCO_2/m^3) of all mixes. This was expected as most of eCO_2 emissions are associated with C content. Binary and ternary cement mixes had lower eCO_2 emissions than control mix. Emissions were decreased as clinker content decreased. This was reported earlier (Limbachiya et al., 2014). The results also agree with an earlier study (Jimenez et al., 2015) that the influence of SP content on the overall eCO_2 emissions is low. Binary mixes had 6.8% and 15.9% reductions for both 90C-10WCA and 80C-20WCA mixes when compared to control mix. This is in agreement earlier study (Oruji et al., 2017) which claimed WCA could be environmentally-effective approach. Ternary mixes were found to reduce eCO_2 emissions by 27.9% and 34.5% than the control mix for 90CEM II/B-S–10WCA and 80CEM II/B-S–20WCA mixes respectively. Results agree with the fact stated by existing studies (Arun et al., 2020; Opiso et al., 2019) that WCA addition could be a sustainable approach. If only production values were considered, reductions could be noted as 10%, 19.9%, 34.4% and 41.5% for 90C-10CA, 80C-20CA, 90CEM II/B-S–10WCA and 80CEM II/B-S–20WCA mixes respectively. However, it is also important to mention that WCA is solely obtained and taken to the proposed site for sieving prior to its use. Thereby, transportation emissions from the waste source to the site is also added in the calculations. The eCO_2 emissions distribution of developed mixes is shown in Fig 8. Fig. 8 shows that production related eCO_2 emissions decreased for binary and ternary mixes due to replacement of high energy intensive cement with low emission waste materials. Emissions associated with transportation is reported as 13.7%, 16.6%, 17.8%, 21.5% and 22.9% for 100C, 90C-10WCA, 80C-20WCA, 90CEM II/B-S–10WCA and 80CEM II/B-S–20WCA mixes respectively. Control mix transportation emissions were calculated as 56.4 kg eCO_2. Transportation mixes for 10% WCA and 20% WCA incorporated mixes were found as 63.8 kg eCO_2 and 61.9 kg eCO_2. This increase in transportation emissions is purely related with WCA transportation to the site.

The relationship between the eCO_2 emissions and 28 d compressive cube strengths was also observed and revealed in Table 8. Control mix had the highest eCO_2 emissions/MPa value while other mixes had lower values. This reduction in per MPa is due to lower eCO_2 emissions of binary and ternary cement mixes compared to control mix. This may also indicate that binder content may be potentially increased to achieve the same design strength with even having less eCO_2 emissions.

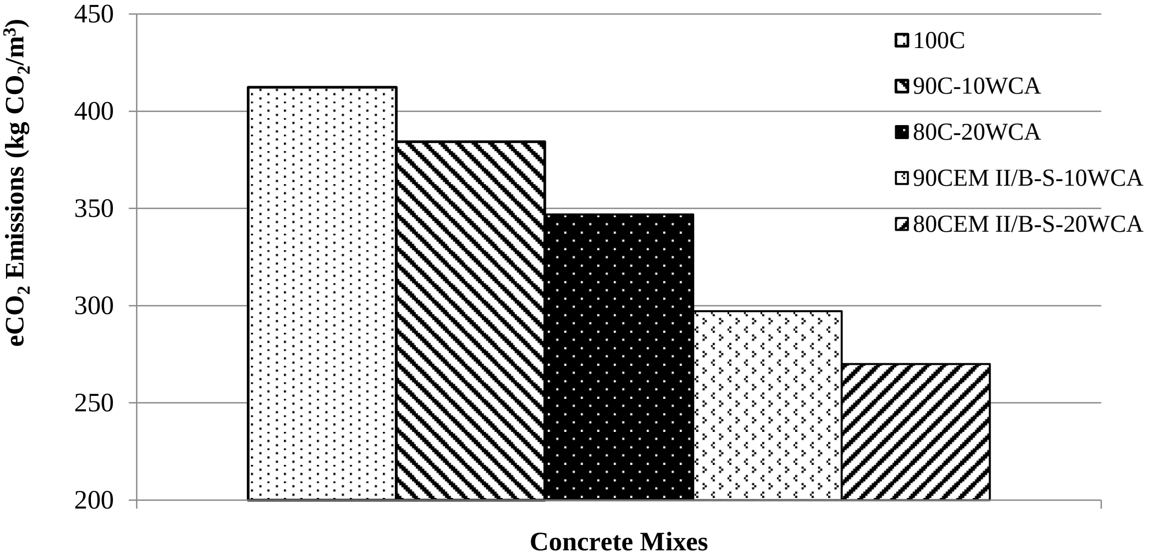

Figure 7. eCO_2 emissions of developed mixes

Figure 7. Bar chart shows the environmental sustainability of the concrete mixes. The eCO_2 emissions, in kg CO_2/m^3, were calculated for the indication of environmental sustainability, calculated considering the quantities of each constituent used, based on the processes revealed earlier in Fig.2.

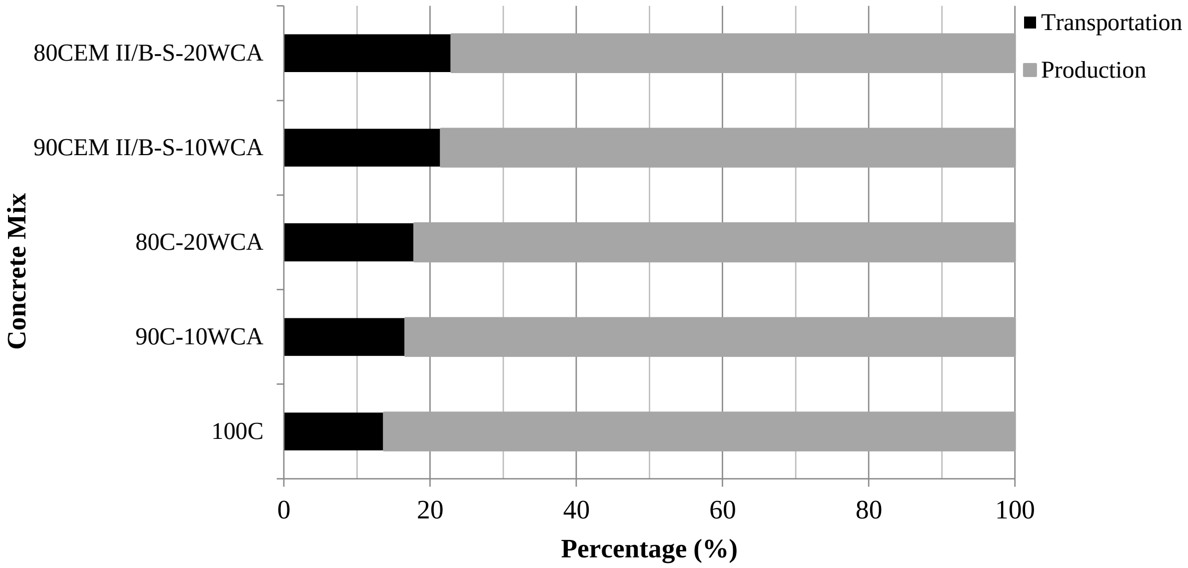

Figure 8. The eCO_2 emissions distribution of developed mixes

Figure 8. Horizontally aligned pair of histogram bars reveals the breakdown of the percentage of the eCO_2 emissions calculations associated with Transportation and Production processes. Mixes are as follows from bottom to up as 100C, 90C-10WCA, 80C-20WCA, 90CEM II/B-S-10WCA, 80CEM II/B-S-20WCA cement mixes. Transportation related percentages are given in black colour while Production related percentages are given in grey colour.

Table 8. The relationship between environmental and economic sustainability and 28 d compressive strength

Concrete Mix	Environmental impact / 28 d compressive strength (kg CO_2 / MPa)	Economic impact / 28 d compressive strength ($ / MPa)
100C	8.7	1.08
90C-10WCA	7.9	0.98
80C-20WCA	8.4	1.07
90CEM II/B-S–10WCA	7.6	1.21
80CEM II/B-S–20WCA	7.3	1.17

3.2.2. Economic Analysis

The cost of developed mixes is presented in Fig. 9. 100C mix had the highest cost amongst all mixes (51.37 $/m^3). WCA utilized binary and ternary mixes had lower cost than control mix. This finding is coherent with earlier studies (Hwang & Cortes, 2021; Rafieizonooz et al., 2017) which stated that the utilization of WCA could lower the cost of concrete. Reductions were found as 7.3% and 14.6% for 90C-10WCA and 80C-20WCA cement mixes while 8.2% and 15.4% for 90CEM II/B-S–10WCA and 80CEM II/B-S–20WCA cement mixes respectively. Higher cost of control mix is due to higher cost of the C. C was replaced with no-cost WCA waste and this reduced the overall cost of concrete even though transportation cost of the WCA to the site is included. The allocation of concrete mixes is given in Fig. 10. Transportation related percentages are found as 20.6%, 22.4%, 23.4%, 22.6% and 23.6% for 90C-10WCA, 80C-20WCA, 90CEM II/B-S–10WCA and 80CEM II/B-S–20WCA cement mixes respectively. These percentages refer to 10.6 $/m^3, 10.7 $/m^3, 10.3 $/m^3, 10.7 $/m^3, 10.3 $/m^3 for these mixes respectively. The reductions were achieved for 20%WCA incorporated mixes while slight increment was noted for 10%WCA incorporated mixes.

The liaison between the cost and 28 d compressive strengths was also observed and revealed in Table 8. 90CEM II/B-S–10WCA cement mix had the highest ratio (1.21) of all mixes which is followed by 80CEM II/B-S–20WCA (1.17). Higher ratios are due to the lower 28d compressive strengths of these mixes. Binary cement mixes had higher 28d compressive cube strengths which also reflected to the ratios of these two mixes and achieved lower cost per MPa compared to control mix.

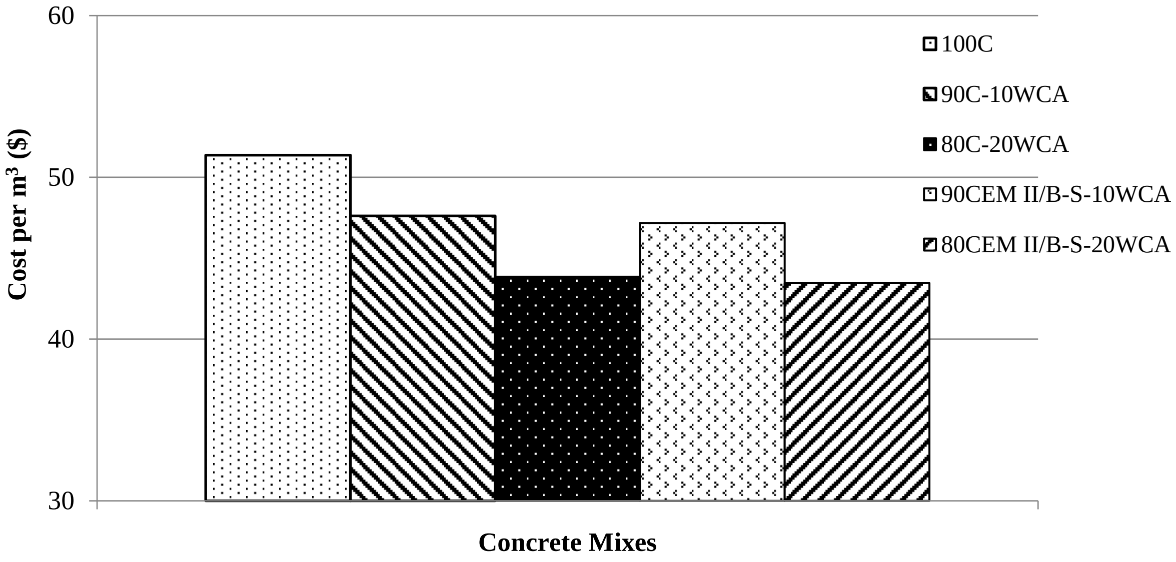

Figure 9. The cost of developed mixes

Figure 9. Bar chart shows the economic sustainability of the concrete mixes based on the cost of the mixes, calculated considering the quantities of each constituent used. Economic sustainability is given in in $/m^3 based on the processes revealed earlier in Fig.2.

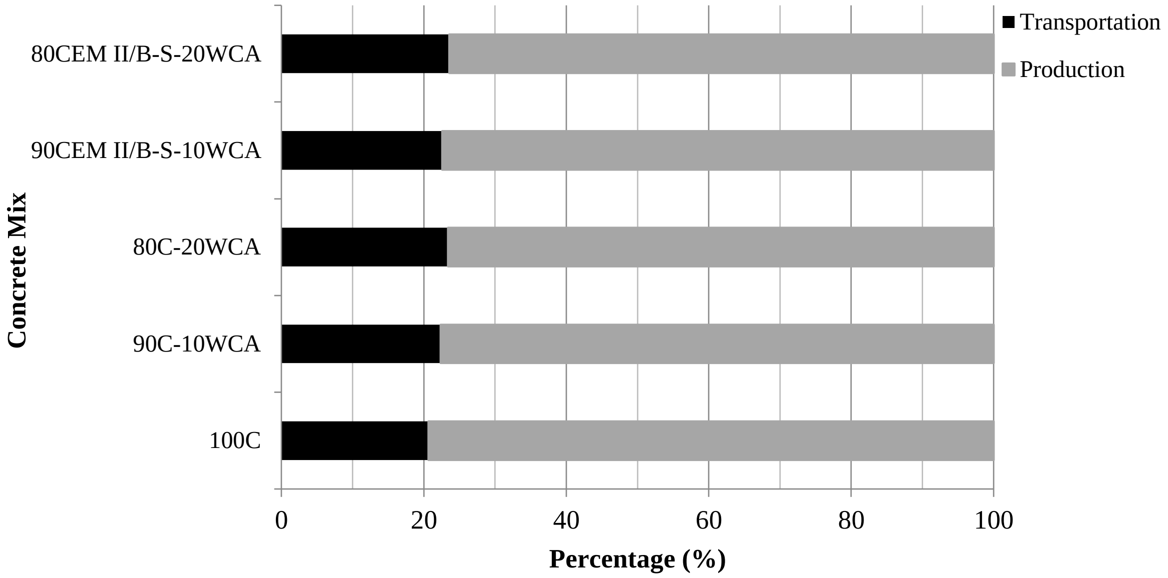

Figure 10. The cost allocation of developed mixes

Figure 10. Horizontally aligned pair of histogram bars reveals the breakdown of the percentage of the cost calculations associated with Transportation and Production processes. Mixes are as follows from bottom to up as 100C, 90C-10WCA, 80C-20WCA, 90CEM II/B-S-10WCA, 80CEM II/B-S-20WCA cement mixes. Transportation related percentages are given in black colour while Production related percentages are given in grey colour.

3.2.3. Social Perspective

3.2.3.1. Sound Permeability

Sound permeability values and index of reduction of impact noise are presented in Table 9. As mentioned earlier, sound permeability values were calculated in percentages through given and received decibels. Index of reduction values were also provided to reveal the sound decibel differences for each mix. Control mix achieved the highest sound permeability of all mixes. Binary and ternary mixes achieved lower values compared to control mix. Binary mixes had lower values than ternary mixes which indicates that WCA inclusion reduces sound absorption compared to GGBS. Even though, ternary mixes had decreased sound absorption values than control mix. Reduced sound absorption for WCA was also reported earlier (Kuo et al., 2013). There is no specific trend observed regarding to the increasing WCA content. Earlier study (Desarnaulds et al., 2005) stated the index of reduction of impact noise between 17-22 dB. The results conform with range identified for sheep wool, wood wool and cellulose materials. Pore structure and density are decisive factors for material's sound absorption (Li and Ren, 2011). The relation between sound permeability and porosity of all mixes was investigated and revealed in Fig. 11 and indicated a very good correlation (R^2=0.95). The importance of the porosity on sound absorption also reported earlier (Oancea et al., 2018). Further relationship between sound permeability and density is given in Fig. 12. whereas correlation was found as R^2=0.83. Results suggest that sound permeability values are more influenced by the pore texture than density. It is believed that pore refinement through pozzolanic reactions by WCA and GGBS, as suggested by compressive strength values, led to a denser matrix through the formation of smaller pores. These smaller pores consequently increased sound absorption resistance for binary and ternary mixes.

Table 9. Sound permeability and reduction index of laboratory mixes

Concrete Mix	Sound Permeability (%)	Standard deviation	Index of reduction of impact noise (dB)
100C	21.9	1.2	19.5
90C-10WCA	18.6	1.3	18.1
80C-20WCA	18.4	1.5	18.0
90CEM II/B-S–10WCA	19.3	1.2	19.2
80CEM II/B-S–20WCA	19.5	1.4	19.4

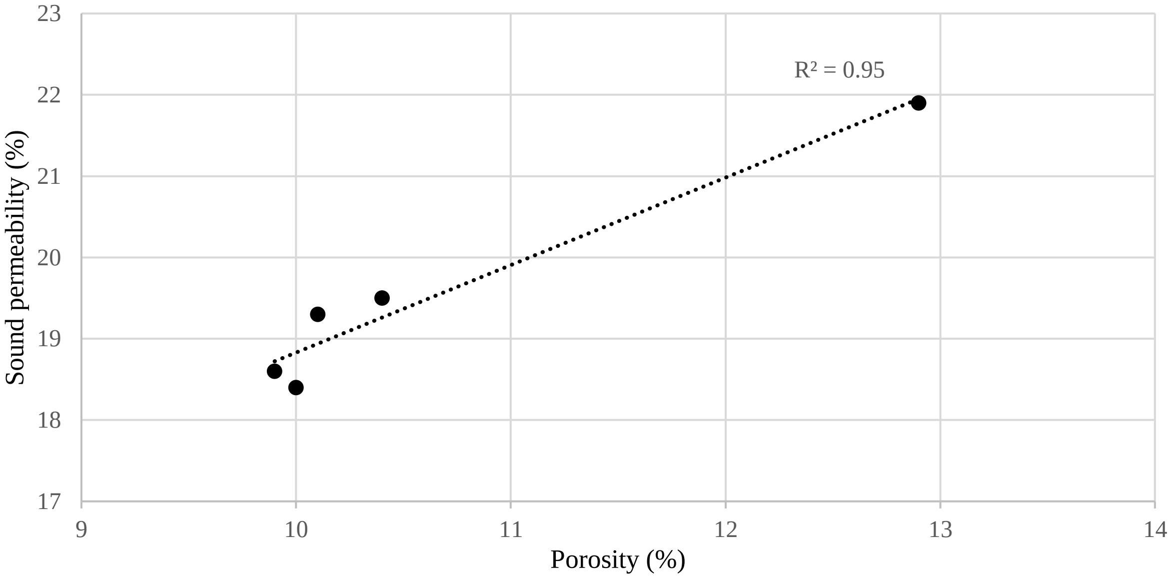

Figure 11. Relationship between Sound Permeability and Porosity

Figure 11. Graphical demonstration shows the correlation between sound permeability (y-axis) and porosity (x-axis) values. A trend-line was added and correlation value was provided as R^2 = 0.95.

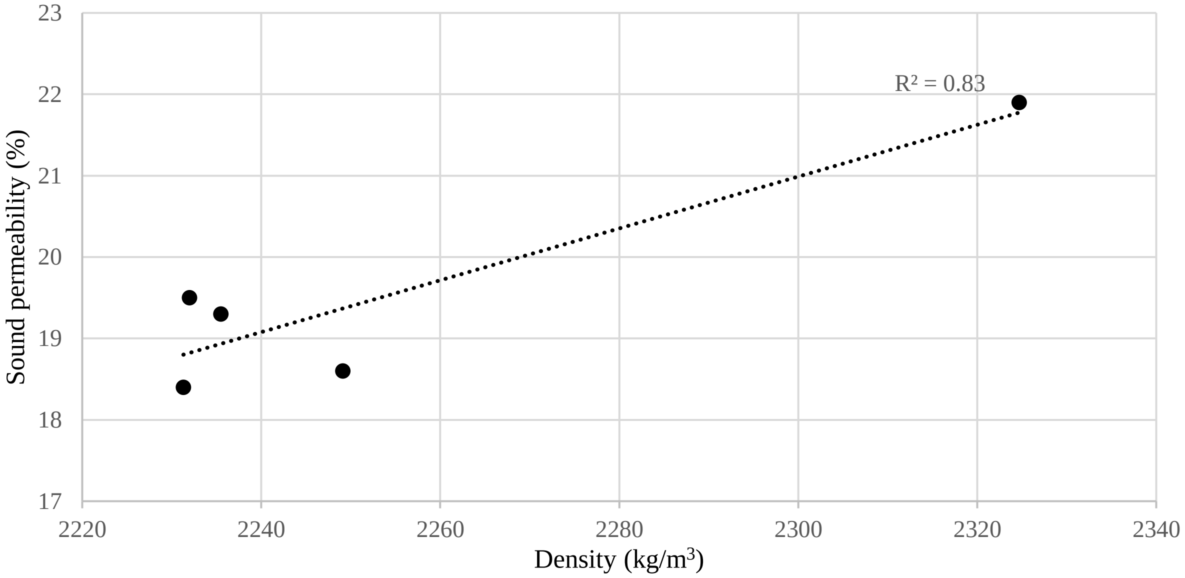

Figure 12. Relationship between Sound Permeability and Density

Figure 12. Graphical demonstration shows the correlation between sound permeability (y-axis) and density (x-axis) values. A trend-line was added and correlation value was provided as $R^2 = 0.83$.

3.2.3.2. Thermal Conductivity

It is important for construction materials to have enhanced thermal mass to provide better insulation. This could support sustainable construction through reducing the operational energy required for heating and cooling, and thus mitigate the CO_2 emissions (The Concrete Centre, 2019). The thermal conductivity results are presented in Table 10. Results showed that control mix had higher thermal conductivity value than binary and ternary cement mixes. Thermal conductivity values were decreased as the WCA content increased. Reduction in thermal conductivity values were also reported earlier due to either increment in porosity (Gooi et al., 2020) or reduction in density (Muthusamy et al., 2020). Lower density binary and ternary cement mixes reported lower thermal conductivity. However, there is no clear trend observed with both density and porosity. As reduction was not fully related to density and porosity, it is believed that WCA possesses thermal-effective nature and reduced thermal conductivity. Previous statement by Venkataraman et al. (2017) found that thermal conductivity is also effected by moisture content and surrounding temperature. 90CEM II/B-S–10WCA and 80CEM II/B-S–20WCA cement ternary mixes had higher thermal values compared to binary mixes. Results also support the fact that as the filling paste ratio is further developed, higher thermal conductivity values were reported (Ngohpok et al., 2018). This can also be seen from the 28d compressive strength results. The results also suggest that higher SP content may lead to dissolved chemical ions in water and thus increased thermal conductivity (Khaliq & Kodur, 2011). In general, lower thermal conductivity of binary and ternary cement mixes may be attributed to WCA and GGBS having amorphous characteristics and decreased thermal conductivity (Demirboga, 2007). It is observed that inherent properties of WCA and GGBS have an influence on the determination of concrete thermal conductivity.

Table 10. Thermal conductivity values of mixes

Concrete Mix	Thermal conductivity (λ (W/mK))
100C	2.3367
90C-10WCA	2.3109
80C-20WCA	2.2453
90CEM II/B-S–10WCA	2.2905
80CEM II/B-S–20WCA	2.2856

3.3. Overall Sustainability Performance

Sustainability is an interconnected concept which includes environmental, economic and social facets. In addition, sustainable concrete needs to be durable. Improved durability prolonges the service life of concrete and lowers the maintenance cost.

For engineering properties, WCA incorporated mixes had lower slump values and this may influence durability and require more compaction for homogenous and dense concrete (Ting et al., 2020) which will inevitably increase emissions and cost associated with casting. WCA in ternary mixes would not require extra compaction. Density results suggest that lighter concrete construction which will eventually reduce the amount of reinforcing bar needed for the design. This will then contribute to sustainable material production. Developed mixes did not achieve the target design strengths at 28d which may have an adverse effect on the concrete durability due to lower pozzolanic activity. This may be diminished by grinding WCA for finer particles which could lead to durable concrete production. Earlier study (Canpolat et al., 2004) also addressed that WCA needs grinding to be used as cement replacement which would also require higher energy demand and lower sustainability credentials. However, strength development rates suggest that WCA could provide pozzolanic reactions and improves pore structure of concrete, as suggested by 56d results, and this could be a promising approach at longer ages from sustainable practices perspective. Permeation properties suggest that developed mixes could improve concrete durability and thus potential service life and thus promotes sustainability.

Environmental and economic sustainability is mostly paid attention due to concerns on the built environment and feasible application respectively while social sustainability is mostly not considered. Gonzalez et al. (2017) stated that CO_2 emissions and cost of energy in each country have a significant effect on the cost and CO_2 emissions for the concrete produced with recycled materials.

Table 11 gives the optimum transportation distances to environmentally-friendly and cost-effective concrete production. It is worth to note that cement is the most used type in concrete production on national basis and result obtained in this could guide local authorities for the implementation of more sustainable approaches. From environmental and economical sustainability perspective, the use of WCA and GGBS in binary and ternary cement combination can potentially reduce concrete CO_2 emissions and cost considerably depending upon the content used. This is in line with previous studies (Arun et al., 2020; Hwang & Cortes, 2021; Opiso et al., 2019; Rafieizonooz, et al., 2017) which stated that WCA use can be used in sustainable concrete production. CEM II/B-S is obtained as blended and therefore, transportation related emissions and cost of cement and CEM II/B-S are the same. For mixes to have the same transportation relevant eCO_2 emissions, WCA should be obtained within the radius of 12 km for 10% replacement level and 23.6 km for 20% replacement level. When only WCA total cost is considered, 98.4% of the cost is associated with transportation. It was also found out that when WCA is used for 10% as a cement replacement, it could be a sustainable approach if it is obtained within 38.5 km range while 123.5 km would be a sustainable approach when WCA content is 20%.

For social sustainability, acoustically-efficient construction material is a part of the sustainable construction practices. Most of the green building assessment tools aims to improve the occupants` life quality and reduce sound related diseases. Therefore, WCA use can be potentially used in sustainable construction applications. Thermal conductivity test results showed that lower thermal conductivity of developed mixes could potentially reduce the energy demand. This could also provide thermal comfort to the occupants which is also an aspect for the green buildings.

Table 11. Optimum transportation distances for the same transportation impact

Mixes	Optimum distance (km)	
	Environmental feasibility	Economical feasibility
90C-10WCA	12	38.5
80C-20WCA	23.6	123.5
90CEM II/B-S – 10WCA	12	38.5
80CEM II/B-S – 20WCA	23.6	123.5

3.4. Balanced Score Model

Mixes were evaluated in terms of engineering performance and sustainability analyses. This section will perform scores based on engineering properties (slump value, hardened density, 28d compressive strength and water permeability) and sustainability analyses (environmental, economic and social sustainability). Thus, nine criteria were considered. The main objective of the scoring system is to provide a general view on the overall performance of the developed concretes. Scoring is carried out based in comparison to control mix. For properties which higher value is known to be better; slump value and compressive strength, score was calculated in percentage compared to control mix. Other properties; hardened density, water permeability, porosity, environmental, economic and social sustainability, were reversely proportioned to control mix as lower values indicate improved performance. Equations for direct and reverse proportions are given in Equation 1a and Equation 1b. Control mix is given value of 100 points for each test. Each property is assumed to have the same weighting. Overall score of mixes were calculated and proportioned to overall score of control mix (900 points). Performance improvement formula is given in Equation 2.

$$\text{Equation (1a) } Performance = \frac{Developed\ mix}{Control\ mix} \times 100$$

$$\text{Equation (1b) } Performance = \frac{Control\ mix}{Developed\ mix} \times 100$$

$$\text{Equation (2) } Performance\ improvement = \frac{Total\ performance\ values\ for\ developed\ mix}{100 \times number\ of\ tests\ (for\ control\ mix)} \times 100$$

Fig 13. shows the overall performance improvements of developed mixes. Binary and cement mixed had improved performances when compared to control mix. As an indicator, control mix is included as zero value. Binary mixes were found to have 10.92% and 11.37% higher values for 90C-10WCA and 80C-20WCA mixes respectively. Ternary mixes were observed to improve overall score by 15.55% and 15.61% for 90CEM II/B-S-10WCA and 80CEM II/B-S-20WCA cement mixes respectively. Increasing WCA content were observed to increase score slightly. Addition to that, CEM II/B-S cement use was also observed to improve overall performance further. Overall higher score of these mixes are mostly attributed to improved water permeability, porosity, environmental analysis, cost analysis and sound permeability performances of these mixes. Score distributions between engineering and sustainability performances are given in Fig. 14. 90C-10WCA cement mix had the highest engineering related score percentage (56.6%) of all mixes. This is followed by control mix (55.6%). Engineering performance percentages were found to be 54.3%, 55.5% and 53.3% for 80C-20WCA, 90CEM II/B-S-10WCA and 80CEM II/B-S-20WCA cement mixes respectively. Engineering related percentage score decreased as the WCA content increased. When comparing counterparts, binary mixes had higher engineering related percentages. Table 12 given the percentage improvements for both engineering and sustainability performances. Increasing WCA was observed to lower engineering performance improvements. In addition, ternary mixes had higher percentage improvement compared to control and binary mixes. Increasing WCA content and using CEM II/B-S cement improved sustainability percentage which was expected due to lowering clinker content.

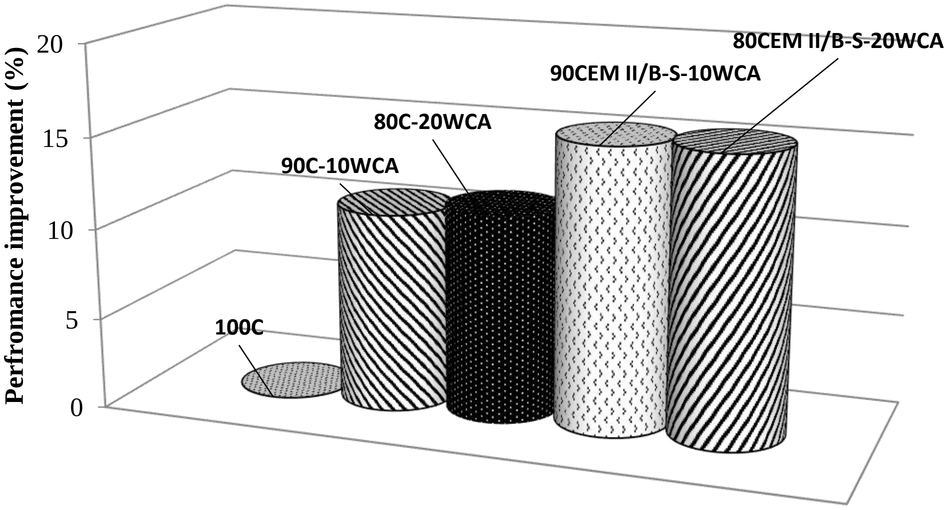

Figure 13. Overall Performance Improvements

Figure 13. 3-D circular columns were used in the bar chart to represent overall score improvement of the laboratory mixes. Control mix, 100C, was taken as reference so value input is given as 0, then overall score improvement based on total score is given in percentages in y-axis.

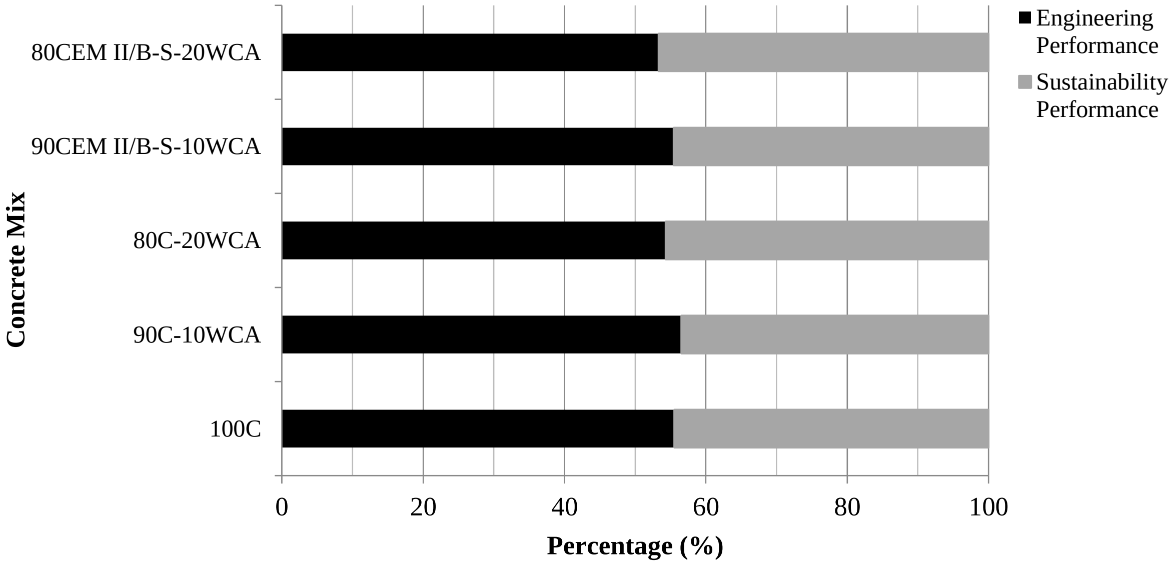

Figure 14. The score distribution of developed mixes

Figure 14. Horizontally aligned pair of histogram bars reveals the breakdown of the percentage of the overall score calculation associated with Engineering and Sustainability Performances. Mixes are as follows from bottom to up as 100C, 90C-10WCA, 80C-20WCA, 90CEM II/B-S-10WCA, 80CEM II/B-S-20WCA cement mixes. Engineering Performance related percentages are given in black colour while Sustainability Performance related percentages are given in grey colour.

Table 12. Engineering and sustainability performance improvement of mixes

Mixes	Percentage improvement (%)	
	Engineering Performance	Sustainability Performance
90C-10WCA	12.93	8.41
80C-20WCA	8.85	14.52
90CEM II/B-S – 10WCA	15.37	15.77
80CEM II/B-S – 20WCA	11.01	21.36

4. Conclusions and Recommendation

This study observed the engineering and sustainability performances of concretes made with binary (90C-10WCA and 80C-20WCA) and ternary (90CEM II/B-S-10WCA and 80CEM II/B-S-20WCA) cements. Furthermore, this study aimed to provide a score model for the overall performance assessments of the developed mixes.

WCA utilization was observed to have negative impact on fresh concrete which may entrap air through its porous nature and require more compaction and energy which may influence concrete sustainability. The use of WCA and GGBS were found to reduce the concrete density significantly (up to 4%) due to lower specific gravity of these materials. This may reduce the requirement for the reinforcement and could lead to material-efficient structural design. In general, developed mixes had lower strength values at all ages except 90C-10WCA cement mix at 56d (3.1% improvement). Early strengths showed dramatic reduction, ranged between 26.3% to 48%, while strength losses were minimized at further ages, ranged between 4% to 20.9% at 28d. Results suggest presence of pozzolanic reactions which led to refinement of pore matrix. Water permeability and porosity results indicated that WCA, even with coarser characteristics than cement, may have led to optimal particle packing and reduced permeability effectively compared to control mix. Permeation properties are consistent with compressive strength results which indicating improved pore structure. This superior pore structure may reduce the rate of penetration of any hazardous materials and thus increase the service life of concrete. This may either reduce or delay the need for the extraction and use of natural raw materials for the new construction purposes and thereby contributes sustainability.

Environmental sustainability was improved as the replacement level of WCA was increased. Environmental impact (eCO_2 emissions) of mixes were decreased significantly as the clinker content reduced (up to 34.5%). Economic sustainability assessments showed that use of WCA and GGBS could reduce the overall cost of concrete considerably. Cost reductions were more obvious for 20% WCA incorporated mixes (up to 15.4%) compared to 10% WCA utilized mixes (up to 8.2%). For mixes to have the same transportation emissions, WCA is feasible for practical use if it is obtained from 12 km and 23.6 km for 10% and 20% replacement levels. The range for the same transportation distances were found as 38.5 km and 123.5 km for 10% and 20% replacement levels respectively. Social sustainability (sound permeability and thermal conductivity) analyses showed the use of binary and ternary cement mixes could provide acoustically-effective construction through sound-absorbing effect of WCA and improved pore structure that increased acoustic resistance. This potentially reduces the need for heating and cooling due to lower thermal conductivity characteristics to the occupants. Thereby, it could be beneficial to use WCA for sustainable concrete construction. Results also showed that sustainability can be successfully implemented if managed thoroughly. In general, the use of WCA in both binary and ternary blend cements could reduce the environmental burden when disposal is considered. It can also reduce the potential contamination of ground water. The amount disposal lands will be a great concern, therefore concrete production could be one of the best options to use and preserve the virgin lands for future generations.

Concrete quality is usually associated with 28d compressive strength. Lower 28d compressive strength of WCA mixes may be a drawback for industrial application. It is recommended to further study WCA concrete mixes with increased binder content to achieve the same 28d design strength for the optimum mechanical and sustainability performances. In addition, engineering and sustainability performances of further grinded WCA particles for finer particles is recommended for further research. Compressive strength, water permeability, porosity and sound permeability tests suggest pore refinement at 28d and 56d due to pozzolanic reactions. Long age (>56d) performances of laboratory mixes should be further studied to acknowledge the behaviour of the WCA incorporated mixes.

Acknowledgement

The author would like to acknowledge individuals; Mrs. Tuğçe Mani, Kemal Sergen and Metin Eray, and collaborating companies; Boğaziçi Endüstri Madencilik Ltd. and KASCON Ready-mix Concrete Company and Nayat Yapı Ltd. for their contribution to this research.

Data Availability Statement

The data that supports the findings of this study are available from the corresponding author, S.B., upon reasonable request.

References

Abbasi, M., & Nilsson, F. (2016). Developing environmentally sustainable logistics: Exploring themes and challenges from a logistics service providers' perspective. *Transportation Research Part D: Transport and Environment*, 273-283.

Akadiri, P., Chinyio, E., & Olomolaiye, P. (2012). Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. *Buildings*, 126-152.

Alderete, N. M., Joseph, A. M., Van den Heede, P., Matthys, S., & De Belie, N. (2021). Effective and sustainable use of municipal solid waste incineration bottom ash in concrete regarding strength and durability. *Resources, Conservation & Recycling*, 105356.

American Society for Testing and Materials (2019) Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. USA: ASTM International.

Ali-Boucetta, T., Behim, M., Cassagnabere, F., Mouret, M., Ayat, A., & Laifa, W. (2021). Durability of self-compacting concrete containing waste bottle glass and granulated slag. *Construction and Building Materials*, 121133.

Andrew, R. M. (2018). Global CO2 emissions from cement production. *Earth System Science Data*, 10, 195-217.

Arenas, C., Vilches, L., Cifuentes, H., Leiva, C., Vale, J., & Fernandez-Pereira, C. (2011). Development of Acoustic Barriers Mainly Composed of Co-combustion Bottom Ash. *World of Coal Ash (WOCA) Conference.* Denver: University of Kentucky.

Arun, N., Singh, P., & Gupta, S. (2020). Utilisation of ground bottom ash in concrete. *Materials Today: Proceedings*, 663-669.

Aydin, E. (2016). Novel coal bottom ash waste composites for sustainable construction. *Construction and Building Materials*, 582-588.

Bajare, D., Bumanis, G., & Upeniece, L. (2013). Coal Combustion Bottom Ash as Microfiller with Pozzolanic Properties for Traditional Concrete. *Procedia Engineering*, 149-158.

Ban, C.B., Jia, L.J., Ping, K.K.L. & Siddique, R. (2022) Properties of ternary blended cement containing ground granulated blast furnace slag and ground coal bottom ash. *Construction and Building Materials*, 315, 125249.

Barbulescu, G., & Lafargue, R. (2016). Improving social sustainability through comfortable outdoor spaces. *Constanta: Transsolar Academy*.

Bhat, J.A. (2021) Mechanical behaviour of self compacting concrete: Effect of wood ash and coal ash as partial cement replacement. *Materials Today: Proceedings*. 42, 1470-1476.

Bostanci, S.C. (2020). Use of waste marble dust and recycled glass sand for sustainable concrete production. *Journal of Cleaner Production*. 119785.

Bostanci, S. C. (2019). Utilisation of wood ash for environmentally friendly concrete production. *Fifth International Conference on Sustainable Construction Materials and*. London: International Committee of the SCMT conferences.

Bostanci, S. C., Limbachiya, M., & Kew, H. (2016). Portland composite and composite cement concretes made with coarse recycled and recycled glass sand aggregates: Engineering and durability properties . *Construction and Building Materials*, 324-340.

Bostanci, S. C., Limbachiya, M., & Kew, H. (2016). Portland slag and composites cement concretes: engineering and durability properties. *Journal of Cleaner Production*, 542-552.

Canpolat, F., Yilmaz, K., Köse, M. M., Sümer, M., & Yurdusev, M. (2004). Use of zeolite, coal bottom ash and fly ash as replacement materials in cement production. *Cement and Concrete Research*, 731-735.

Cheng, B., Liu, R., Li, X., Castillo, E.D.R., Chen, M., & Li, S. (2022) Effects of fly and coal bottom ash ratio on backfill material performance. *Construction and Building Materials*, 319, 125831.

Cheriaf, M., Cavalcante Rocha, J., & Pera, J. (1999). Pozzolanic properties of pulverized coal combustion bottom ash. *Cement and Concrete Research*, 1387-1391.

Climate Change Secretariat. (2008). *Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount*. Bonn: United Nations Framework Convention on Climate Change.

de Brito, J., & Kurda, R. (2021). The past and future of sustainable concrete: A critical review and new strategies on cement-based materials. *Journal of Cleaner Production*, 123558.

Demirboga, R. (2007). Thermal conductivity and compressive strength of concrete incorporation with mineral admixtures. *Building and Environment*, 2467-2471.

Desarnaulds, V., Costanzo, E., Carvalho, A., & Arlaud, B. (2005). Sustainability of acoustic materials and acoustic characterization of sustainable materials. *Proceedings of the 12th International Congress on Sound and Vibration*, (pp. 1-8). Lisbon.

Ding, T., Xiao, J., & Tam, V. W. (2016). A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. *Waste Management*, 56, 367-375.

EPRS. (2018). *European Parliament*. Retrieved from CO2 standards for new cars and vans: https://www.europarl.europa.eu/RegData/etudes/BRIE/2018/614689/EPRS_BRI%282018%29614689_EN.pdf

Erdem, T. K., & Kırca, Ö. (2008). Use of binary and ternary blends in high strength concrete. *Construction and Building Materials*, 1477-1483.

Federal Highway Administration. (2016). *Strategies for Improving Sustainability of Concrete Pavements*. Washington: US Department of Transportation.

Flegar, M., Serdar, M., Londono-Zuluag, D., & Scrivener, K. (2020). Regional Waste Streams as Potential Raw Materials for Immediate Implementation in Cement Production. *Materials*, 5456.

Gonzalez, M., Navarrete, I., Arroyo, P., Azua, G., Mena, J., & Contreras, M. (2017). Sustainable decision-making through stochastic simulation: Transporting vs. recycling aggregates for Portland cement concrete in underground mining projects. *Journal of Cleaner Production*, 1-10.

Gooi, S., Mousa, A. A., & Kong, D. (2020). A critical review and gap analysis on the use of coal bottom ash as a substitute in concrete. *Journal of Cleaner Production*, 121752.

Hafez, H., Kassim, D., Kurda, R., Silva, R., & de Brito, J. (2021). Assessing the sustainability potential of alkali-activated concrete from electric arc furnace slag using the ECO2 framework. *Construction and Building Materials*, 122559.

Haibin, L., & Zhenling, L. (2010). Recycling utilization patterns of coal mining waste in China. *Resources, Conservation and Recycling*, 1331-1340.

Hajek, P. (2017). Concrete Structures for Sustainability in a Changing World. *Procedia Engineering*, 207-214.

Hammond, G., & Jones, C. (2011). *Embodied Carbon - The Inventory of Carbon and Energy (ICE).* Bracknell: Building Services Research and Information Association.

Hanafi, M., Aydin, E., & Ekinci, A. (2020). Engineering Properties of Basalt Fibre-Reinforced Bottom Ash Cement Paste Composites. *Materials*, 1952.

Hannan, N., Shahidan, S., Ali, N., Bunnori, N. M., Zuki, S., & Ibrahim, M. (2020). Acoustic and non-acoustic performance of coal bottom ash concrete as sound absorber for wall concrete. *Case Studies in Construction Materials*, e00399.

Hasim, A.M., Shahid, K.A., Ariffin, N.F., Nasrudin, N.N., & Zaimi, M.N.S. (2022). Properties of high volume coal bottom ash in concrete production. *Materials Today: Proceedings*. 48. 1861-1867.

Hossain, M., Cai, R., Ng, T., Xuan, D., & Ye, H. (2021). Sustainable natural pozzolana concrete - A comparative study on its environmental performance against concrete with other industrial by-products. *Construction and Building Materials*, 121429.

Huising, D., Zhang, Z., Moore, J. C., Qiao, Q., & Li, Q. (2015). Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling. J. Clean. Prod., 1-12.

Hwang, S. S., & Cortes, C. M. (2021). Properties of mortar and pervious concrete with co-utilization of coal fly ash and waste glass powder as partial cement replacements. *Construction and Building Materials*, 121415.

International Maritime Organization. (2014). *Third IMO Greenhouse Gas Study 2014*. Suffolk: International Maritime Organization.

Jang, J., Kim, H., Kim, H., & Lee, H. (2016). Resistance of coal bottom ash mortar against the coupled deterioration of carbonation and chloride penetration. *Materials and Design*, 160-167.

Jiao, W., Sha, A., Liu, Z., Li, W., Jiang, W., Qin, W., & Hu, Y. (2020). Study on thermal properties of steel slag asphalt concrete for snow-melting pavement. *Journal of Cleaner Production*, 123574.

Jimenez, C., Barra, M., Josa, A., & Valls, S. (2015). LCA of recycled and conventional concretes designed using the Equivalent Mortar Volume and classic methods . *Construction and Building Materials*, 245-252.

Jindal, B., Jangra, P., & Garg, A. (2020). Effects of ultra fine slag as mineral admixture on the compressive strength, water absorption and permeability of rice husk ash based geopolymer concrete. *Materials Today: Proceedings*, 871-877.

Kansal, C. M., & Goyal, R. (2021). Analysing mechanical properties of concrete with nano silica, silica fume and steel slag. *Materials Today: Proceedings*.

Kaplan, R. S., & Norton, D. P. (1991). The Balanced Scorecard - Measures that Drive Performance. *Hardvard Business Review*, 70-80.

Kaur, H., Siddique, R., & Rajor, A. (2019) Influence of incinerated biomedical waste ash on the properties of concrete. *Construction and Building Materials*. 226, 428-441.

Kaza, S., Yao, L., Bhada-Tata, P., & Woerden, F. V. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.* Washington: International Bank for Reconstruction and Development.

Khaliq, W., & Kodur, V. (2011). Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures. *Cement and Concrete Research*, 1112-1122.

Khan, S.U., Nuruddin, M.F., Ayub, T. & Shafiq, N. (2014) Effects of Different Mineral Admixtures on the Properties of Fresh Concrete. *The Scientific World Journal*. 986567.

Khongpermgoson, P., Boonlao, K., Ananthanet, N., Thitithananon, T., Jaturapitakkul, C., Tangchirapat, W., & Ban, C. (2020). The mechanical properties and heat development behaviour of high strength concrete containing high fineness coal bottom ash as a pozzolanic binder. *Construction and Building Materials*, 119239.

Kim, H. K., Jeon, J. H., & Lee, H. K. (2012). Flow, water absorption, and mechanical characteristics of normal and high-strength mortar incorporating fine bottom ash aggregates. *Construction and Building Materials*, 249-256.

Koshy, N., Dondrob, K., Hu, L., Wen, Q., & Meegoda, J. (2019). Synthesis and characterization of geopolymers derived from coal gangue, fly ash and red mud. *Construction and Building Materials*, 287-296.

Kumar, P., & Singh, N. (2020). Influence of recycled concrete aggregates and Coal Bottom Ash on various properties of high volume of fly ash-self compacting concrete. *Journal of Building Engineering*, 101491.

Kuo, W.-T., Liu, C.-C., & Su, D.-s. (2013). Use of washed municipal solid waste incinerator bottom ash in pervious concrete. *Cement and Concrete Composites*, 328-335.

Kurama, H., & Kaya, M. (2008). Usage of coal combustion bottom ash in concrete mixture. *Construction and Building Materials*, 1922-1928.

Leo Samuel, D., Dharmasastha, K., Shiva Nagendra, S., & Prakash Maiya, M. (2017). Thermal comfort in traditional buildings composed of local and modern construction materials. *International Journal of Sustainable Built Environment*, 463-475.

Li, Y., & Ren, S. (2011) Basic Properties of Building Decorative Materials. *Woodhead Publishing Series in Civil and Structural Engineering*. ISBN: 9780857092571, 10-24.

Li, J., & Wang, J. (2019). Comprehensive utilization and environmental risks of coal gangue: A review. *Journal of Cleaner Production*, 117946.

Limbachiya, M., Bostanci, S., & Kew, H. (2014). Suitability of BS EN 197-1 CEM II and CEM V cement for production of low carbon concrete. *Construction of Building Materials*, 397-405.

Liu, Y., Tang, W., & Singh, R. (2019). Study on Compressive Strength and Water Permeability of Steel Slag-Fly Ash Mixed Permeable Brick. *Applied Sciences*, 1-11.

Mangi, S. A., Ibrahim, M. W., Jamaluddin, N., Arshad, M., & Jaya, R. P. (2019). Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material. *Engineering Science and Technology, an International Journal*, 515-522.

Martinez-Lage, I., Vazquez-Burgo, P., & Velay-Lizancos, M. (2020). Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: Technical, economic and environmental analysis. *Waste Management*, 9-19.

Megat Johari, M., Brooks, J. J., Kabir, S., & Rivard, P. (2011). Influence of supplementary cementitious materials on engineering properties of high strength concrete. *Construction and Building Materials*, 2639-2648.

Mishra, G. (2020). *Elements or Components of Green Building-Material, Water, Energy Health*. Retrieved June 29, 2020, from The Constructor – Civil Engineering Home for Civil Engineers: https://theconstructor.org/building/elements-of-green-building/5375/

Mosaberpanah, M. A., Eren, O., & Tarassoly, A. R. (2019). The effect of nano-silica and waste glass powder on mechanical, rheological, and shrinkage properties of UHPC using response surface methodology. *Journal of Materials Research and Technology*, 804-811.

Mostofinejad, D., Khademolmomenin, M., & Tayebani, B. (2021). Evaluating durability parameters of concrete containing limestone powder and slag under bacterial remediation. *Journal of Building Engineering*.

Muthusamy, K., Jamaludin, N. A., Kamaruzzaman, M. N., Ahmad, M. Z., Zamri, N. A., & Budiea, A. A. (2021). Compressive strength of palm oil clinker lightweight aggregate concrete containing coal bottom ash sand replacement. *Materials Today: Proceedings*.

Muthusamy, K., Rasid, M. H., Isa, N. N., Hamdan, N. H., Jamil, N. A., Budiea, A. A., & Ahmad, S. W. (2021). Mechanical properties and acid resistance of oil palm shell lightweight aggregate concrete containing coal bottom ash. *Materials Today: Proceedings*.

Muthusamy, K., Rasid, M. H., Jokhio, G. A., Budiea, A., Hussin, M. W., & Mirza, J. (2020). Coal bottom ash as sand replacement in concrete: A review. *Construction and Building Materials*, 117507.

Nakamura, K., Inoue, Y., & Komai, T. (2021). Consideration of strength development by three-dimensional visualization of porosity distribution in coal fly ash concrete. *Journal of Building Engineering*, 101948.

Neville, A. (2008). *Properties of Concrete.* Essex: Pearson Education Limited.

Ngohpok, C., Satiennam, T., Klungboonkrong, P., & Chindaprasirt, P. (2018). Mechanical Properties, Thermal Conductivity, and Sound Absorption of Pervious Concrete Containing Recycled Concrete and Bottom Ash Aggregates. *KSCE Journal of Civil Engineering*, 1369-1376.

Oancea, I., Bujoreanu, C., Budescu, M., Benchea, M., & Granidaru, C. M. (2018). Considerations on sound absorption coefficient of sustainable concrete with different waste replacements. *Journal of Cleaner Production*, 301-312.

Opiso, E. M., Supremo, R. P., & Perodes, J. R. (2019). Effects of coal fly ash and fine saw dust on the performance of pervious concrete. *Heliyon*, e02783.

Oruji, S., Brake, N. A., Nalluri, L., & Guduru, R. K. (2017). Strength activity and microstructure of blended ultra-fine coal bottom ash-cement mortar. *Construction and Building Materials*, 317-326.

Pavlikova, M., Zemanova, L., Pokorny, J., Zaleska, M., Jankovsky, O., Lojka, M., . . . Pavlik, Z. (2018). Valorization of wood chips ash as an eco-friendly mineral admixture in mortar mix design. *Waste Management*, 89-100.

Petrini, M., & Pozzebon, M. (2009). Managing sustainability with the support of business intelligence: Integrating socio-environmental indicators and organisational context . *Journal of Strategic Information Systems*, 178-191.

Plati, C. (2019). Sustainability factors in pavement materials, design, and preservation strategies: A literature review. *Construction and Building Materials*, 539-555.

Prabagar, S., Subasinghe, K., & Fonseka, K. W. (2015). Wood Ash as an Effective Raw Material For Concrete Blocks. *International Journal of Research in Engineering and Technology*, 228-233.

Purnell, P., & Black, L. (2012). Embodied carbon dioxide in concrete: Variation with common mix design parameters. *Cement and Concrete Research*, 874-877.

Rafieizonooz, M., Salim, M. R., Mirza, J., Hussin, M. W., Salmiati, Khan, R., & Khankhaje, E. (2017). Toxicity characteristics and durability of concrete containing coal ash as substitute for cement and river sand. *Construction and Building Materials*, 234-246.

Rekha, S., Jagadheeswari, Arunprasath, & Sumathy . (2021). Durability properties of copper slag and fly ash based concrete for a sustainable environment. *Materials Today: Proceedings*, 2535-2541.

Rossit, G., & Lawson, M. (2012, September 21). Material LIFE: The Embodied Energy of Building Materials. Toronto.

Sanal, I. (2018). Significance of Concrete Production in Terms of Carbondioxide Emissions- Social and Environmental Impacts. *Journal of Polytechnic*, 369-378.

Santos, B., Limbourg, S., & Carreira, J. (2015). The impact of transport policies on railroad intermodal freight competitiveness – The case of Belgium. *Transportation Research Part D: Transport and Environment*, 230-244.

Scope, C., Vogel, M., & Guenther, E. (2021). Greener, cheaper, or more sustainable: Reviewing sustainability assessment of maintenance strategies of concrete structures. *Sustainable Production and Consumption*, 838-858.

Service, E. P. (2018). *CO2 standards for new cars and vans.* Retrieved from European Parliament: https://www.europarl.europa.eu/RegData/etudes/BRIE/2018/614689/EPRS_BRI%282018%29614689_EN.pdf

Shanmugan, S., Deepak, V., Nagaraj, J., Jangir, D., Jegan, S., & Palani, S. (2020). Enhancing the use of coal-fly ash in coarse aggregates concrete. *Materials Today: Proceedings*, 174-182.

Shishkin, A., Aguedal, H., Goel, G., Peculevica, J., Newport, D., & Ozolins, J. (Journal of Cleaner Production). Influence of waste glass in the foaming process of open cell porous ceramic as filtration media for industrial wastewater. *2021*, 124546.

Siddique, R. (2012). Utilization of wood ash in concrete manufacturing, *Resour. Conserv. Recycl*. 67, 27-33. https://doi.org/10.1016/j.resconrec.2012.07.004.

Singh, N., Haque, M.M., & Gupta, A. (2022) Reviewing mechanical performance of geopolymer concrete containing coal bottom ash. *Materials Today: Proceedings*. 65, 1449-1458.

Singh, N., Milhutraj, M., & Arya, S. (2018). Influence of coal bottom ash as fine aggregates replacement on various properties of concretes: A review. *Resources, Conservation & Recycling*, 257-271.

Teng, S., Lim, T., & Divsholi, B. (2013). Durability and mechanical properties of high strength concrete incorporating ultra fine Ground Granulated Blast-furnace Slag. *Construction and Building Materials*, 875-881.

The Concrete Centre. (2018). *Concrete Industry Sustainability Performance Report.* London: MPA The Concrete Centre.

The Concrete Centre. (2019). *Thermal mass explained.* London: MPA The Concrete Centre.

The Concrete Centre. (2020). *Specifying Sustainable Concrete.* London: MPA The Concrete Centre.

Thi, N. N., Truong, S. B., & Minh, N. D. (2021). Reusing coal ash of thermal power plant in a pavement base course. *Journal of King Saud University - Engineering Sciences*.

Timperley, J. (2018, September 13). *Why cement emissions matter for climate change*. Retrieved June 29, 2020, from Carbon Brief => Clear on Climate: https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change

Ting, T., Rahman, M., & Lau, H. (2020). Sustainable lightweight self-compacting concrete using oil palm shell and fly ash. *Construction and Building Materials*, 120590.

Ulubeyli, G. Ç., Bilir, T., & Artir, R. (2017). Ceramic wastes usage as alternative aggregate in mortar and concrete. *Periodicals of Engineering and Natural Sciences*, 194-201.

United Nations. (2015, December 12). Paris Agreement. Paris, France: United Nations. Retrieved June 28, 2020

Venkataraman, M., Mishra, R., & Militky, J. (2017). Comparative analysis of high performance thermal insulation materials. *Journal of Textile Engineering & Fashion Technology*, 401-409.

World Green Building Council. (2020). *Rating tools - World Green Building*. Retrieved June 29, 2020, from Home - World Green Building: https://www.worldgbc.org/rating-tools

Yüksel, İ., Bilir, T., Topcu, İ. B., & Gencel, O. (2017). Effects of bottom ash and granulated blast furnace slag as fine aggregate on abrasion resistance of concrete. *Science and Engineering Composite Materials*, 261-69.

Zuo, J., Jin, X.-H., & Flynn, L. (2012). Social Sustainability in Construction - An Explorative Study. *International Journal of Construction Management*.