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Mechanical performance of green concrete produced with untreated coal waste aggregates

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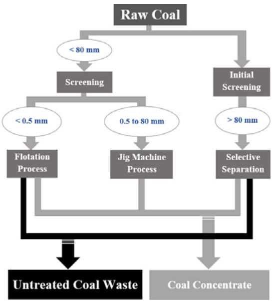
HIGHLIGHTS

- Workability of green concrete specimens remained constant by increasing UCW.
- Overall, replacing 5% of aggregates with UCW improved green concrete properties.
- Unit weight and tensile strengths decreased with increasing UCW contents.
- Maximum modulus of elasticity due to replacing 5% of aggregates with UCW.
- Use of UCW in green concrete is an environmental solution to recycle coal wastes.

GRAPHICAL ABSTRACT



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ABSTRACT

Recently, researchers have tried to find ways to reduce the negative effects of untreated coal wastes (UCW) on the ecosystem of the region. Recycling untreated coal wastes can however be identified as a practical solution in producing concrete aggregates. The present study investigates the mechanical properties of green concrete having untreated coal wastes. A total of eleven mix designs with different contents of untreated coal waste as aggregates were prepared and the cube, cylinder and prism compressive, tensile and flexural strengths as well as the elastic modulus of specimens were determined. The results revealed that untreated coal waste particles can potentially be reused in manufacturing concrete aggregates. It was also confirmed that selecting an appropriate amount of replacement can contribute to the property improvement of concrete, also suggesting an environmental solution to reducing untreated coal wastes. Therefore, replacing 5% of the aggregate with untreated coal wastes instead of sand and gravel, the mechanical properties increased. On average, in sand and gravel replacement compressive and flexural strength increased about 3–7% and 5–8%, respectively.

1. Introduction

As industry and technology are developing and human population is growing, global solid waste generation is accelerating. Generally, there are three methods of disposing such materials, i.e. burial, incinerate and recycling [1]. A number of studies have considered the feasibility of utilizing recycled waste materials in

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the civil engineering discipline [3–7]. Untreated coal is regarded as a significant source of energy on earth and is widely used in various practices. However, coal extraction results in generation of waste material which is not treated because of its high economic costs.

Specific regulations have already been set on the efficient reuse of waste materials and by-products via some of the societies, so as to conserve natural resources [8]. Waste material is any kind of by-products generated by human or industrial activity without any lasting value [9]. Various types of waste materials have been utilized as secondary construction materials. Due to the high potential of waste materials for producing environmental pollution, issues related to isolation and monitoring measures have been addressed [10]. Several investigations have cited the benefits of coal combustion products in highway construction in the U.S. Nevertheless, findings have not proved that these products may jeopardize human health or significantly pose a risk to the environment [11].

Thanaya [12], studying the consequences of coal ash on the hot and cold mix asphalts, noticed the merits of incorporating coal ash in both cold and hot mix asphalts as a filler material. They asserted that hot and cold blends, mixed with coal ash, can be implemented in districts with low to medium traffic densities and the sidewalks. Verma [13] examined the viability of using waste material by-products in making ash bricks. They stated that the prism strength of coal ash masonry bricks is higher respecting the conventional ones.

According to previous studies, numerous applications have taken the advantage of untreated coal waste in construction materials, stabilizing soil, pavement concrete blocks and blended cement. Dos Santos [14] determined the appropriate amount of coal waste as a replacement of fine aggregate in pavement blocks. The characteristics of products generated in the hydration process of quaternary blended cement was inspected by Opiso [15]. The mentioned cement was developed through blending lime sludge, rice hull ash, and coal fly ash. The compressive strength and the amount of Portlandite phases were demonstrated to be reduced, but the porosity increased as to plain hardened cement paste. Investigators have used untreated coal waste materials for engineering applications, for instance, in hot mix asphalt, recycled asphalt mixtures and clay stabilization [16–19]. Kinuthia [20] explored the effect of untreated coal waste as a base and subbase stabilizer. It was then inferred that incorporating coal waste increased the compressive strength of the stabilized materials at different ages. However, aggregate particles with sizes larger than 4.75 mm are very absorptive and cannot acquire cement as a proper coating. About half of the cycles of a control mix face freeze-thaw failures. Thereby, coal waste has to be incinerated first in order to use such aggregates in hot mix asphalt [21].

The effect of adding waste material on the properties of high-strength and conventional concrete has been argued by many researchers [22–30]. In their study, Aiello [31] investigated the properties of recycled tire in fresh and hardened concrete. The results showed that by substituting waste tire rubber particles by 25, 50 and 75% volume of natural fine aggregate in concrete, the flexural strength decreased by 4.49, 5.81 and 7.3%, respectively. It was believed that replacing 75% of tire particles for natural fines by volume increased the energy absorption. Rahmani [2] explored the behavior of PET-incorporated concrete with 5, 10, and 15% partial substitution of sand volume with water-to-cement ratios 0.42 and 0.54. Findings confirmed that the addition of 5% PET in w/c = 0.42 and 0.54, respectively escalated the flexural strength by 6.71 and 8.02%. As PET percentage further increased, flexural strength decreased marking 14.7 and 6.25% drop for the respective w/c ratios with PET amount of 15%.

Frias [32] proposed mixed cement enhanced with active coal waste (ACW). Since compressive strength was reduced, no considerable processing time was noticed, although untreated coal waste was heated at 6500 C for two hours, and then replaced by 10 and 20 percent of the mass. It was noticed that the 7-day compressive strength was escalated, yet 28- and 90-day ones were declined.

Cassiano [33] investigated the impact of untreated coal waste on the concrete at replacement levels of 25, 50, 75 and 100 percent. It was observed that the mechanical resistance of specimens with 25 and 50 percent coal content increased at the age of 28 days. Modarres [16-19] had been working on using this wastage in road construction as filler in asphalts since 2014. They turned the waste untreated coal powder into ash, and then it was used as filler at various percentages in warm asphalt mixtures. The waste materials upgraded the properties of mixtures, and were subsequently implemented in recycled asphalt mixtures and stabilization of clay using wastage and lime in 2016.

The notion of utilizing untreated coal waste materials as aggregates in the concrete industry is still a novel research line. As a consequence, the current study aims at obtaining a sustainable cost-effective approach in employing untreated coal waste materials as suitable alternatives of sand and gravel of concrete mixtures. The proposed approach explores the mechanical properties of cube, cylinder and prism specimens cast with concrete at various curing ages with 0, 5, 10, 15, 20 and 25 percent of sand and gravel replacement.

2. The role of waste materials recycling in sustainable development

These days the amount of waste materials is on the rise and it is highly important to recycle them as far as possible. On the other hand, since concrete is one of the main materials in most construction projects, many researches have been conducted in this area on various types of concrete and even cement for different purposes such as improving the nanostructure, the physical and mechanical properties, reinforcement, durability, life cycle and sustainability [34–45]. Nowadays, many researchers [46–51] are doing their best to find the best solution so as to recycle many waste materials- in particular, in the concrete industry- in order to contribute to the environmental issues. They [22–31,52–58] have, fortunately, made major strides for sustainable development in construction industry and have achieved some promising results in this regard. Based on these findings [22–31,46–58], green concrete can be considered as a suitable solution in this context.

2.1. Steps in producing coal waste

Making coal ready to be used involves processes like regulation, gradation and downgrading of some minerals such as ash, so as to improve the quality of the product. Screening, cleaning, crushing and segregating are considered to be as the main steps. The two conventional techniques are the gravity concentration (Jig) and floatation used in the preparation of a range of coal particle sizes [59]. Gravity concentration is employed to produce coarse and intermediate sizes of coal, and the floatation method is implemented to generate fine size coal. Representation of the coal washing procedure is depicted in Fig. 1.

Once raw coal is mixed and crushed via a special instrument, it is screened and portioned into two. The first portion make up coal pieces of sizes greater than 80 mm, which should be reprocessed. The other portion embraces coal pieces of maximum size of 80 mm which are conveyed to the screening process. Particles with size 0.5–80 mm are transported to the Jig machine, in which a fraction is turned into coal concentrate and the rest is dumped. Finally, particles of size less than 0.5 mm are passed to be treated in the

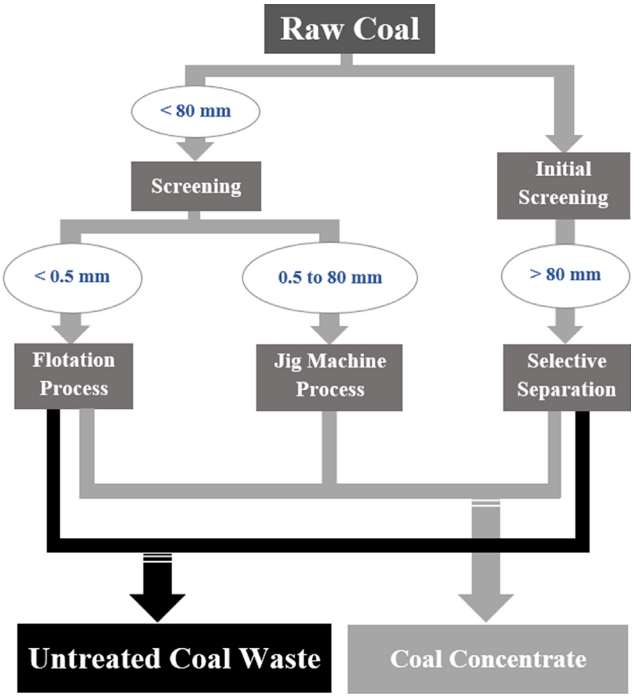


Fig. 1. The schematic of a coal washing plant.

flotation unit, where again a fraction is turned into coal concentrate and the rest is dumped.

2.2. Environmental effects of the coal waste

Coal is regarded as a significant energy source on earth, and its annual production is estimated to hit over 5.5 billion tons all over the globe. The annual share of Iran in the coal production is around 310 million tons.

In the present research, waste and disposed materials were gathered from a plant located in the northern Iran (Alborz Markazi Untreated Coal Factory). As shown in Fig. 2, about 2 million tons of waste is deposited in the vicinity, which is seriously increasing as the result of continuous excavations. The disposed material is dumped in a mountain forest, where the rainfall is anticipated to spread the pollution throughout the region, giving rise to various environmental issues which is about to blemish habitat and contaminate groundwater [60].

The effect of coal waste on the environment is considerable because it can create erosion, leakage of pollutants into groundwater, air pollution and land use limitation [61,62]. It is also considered as a major cause of water pollution [63]. Furthermore, it can adversely influence biodiversity thru emitting organic compounds into soil [64]. Burning coal sludge because of its low amount of energy also pollutes the atmosphere [65].

In addition, pyrite oxidation mechanism is a great concern prompted by the coal waste. Acidic water is produced in the oxidation process when pyrite and an iron-bearing mineral are exposed to air, water or both.

Consequently, the leakage of this liquid, which is often generated at the coal washing plants area, and known as the acid mine drainage (AMD), is so perilous regarding water pollution. AMD is compose of high levels of iron sulfate and sulfur dioxide, which might seriously infect the groundwater through metal poisoning [66–68].

Drainage originated from coal waste dumps has dangerous impacts on the quality of underground water. Ardejani [61] demonstrated pyrite oxidation and generation of AMD in a coal washing factory in Iran. Moreover, they indicated physical changes in the water stream in another coal washing factory. Application of coal wastes in different industries such as construction of highways can be a good solution for these environmental problems.

3. Materials

3.1. Aggregates

The maximum size of gravel in the experimental program was 12.5 mm. The dry weight per volume of gravel was 1570 kg/m^3. Sand Equivalent (SE) value was 82%. Gradation curves of fine and coarse aggregates comply with ASTM C33 [69] standard limits, shown in Fig. 3. In addition, Table 1 summarizes the aggregate properties.

3.2. Cement

The Portland cement type II, which is produced in Mazandaran Cement Factory in northern Iran was used. Tables 2 and 3 respectively report the chemical and physical properties of the cement.

Fig. 2. Deposit of untreated coal waste in Alborz Markazi coal washing plant.

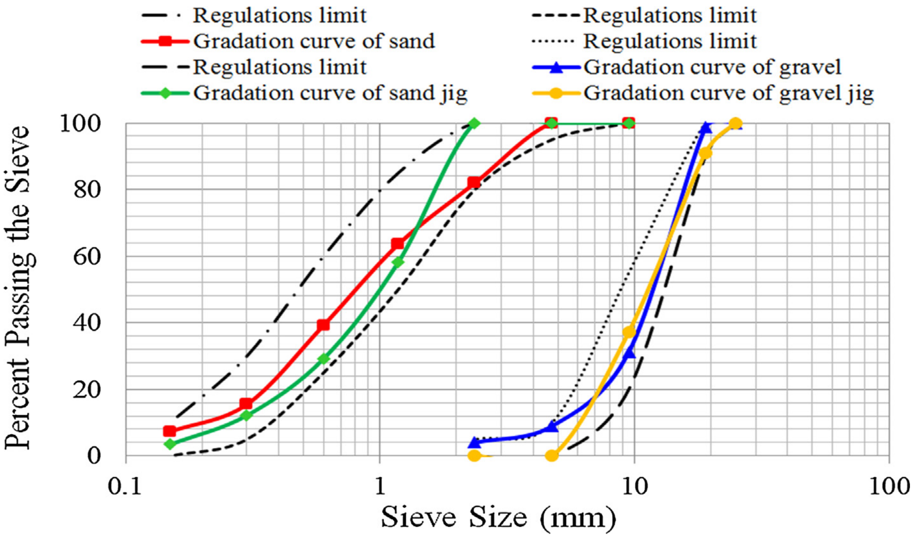


Fig. 3. Gradation curves of aggregate and untreated coal waste.

Table 1
Properties of aggregates.

Aggregate	Gravel	Sand
Specific gravity (g/cm^3)	2.5	2.76
Unit weight (kg/m^3)	1570	1730
Moisture content (%)	0.14	0.3
Moisture of saturated surface dry (%)	0.4	0.5
Fines modulus (FM)	–	2.92
Sand equivalent value (SE) (%)	–	82

Table 2
Chemical properties of cement and untreated coal waste.

Component	Untreated coal waste	Cement
SiO_2 (%)	37.8	21.90
Al_2O_3 (%)	13.14	4.86
Fe_2O_3 (%)	2.85	3.30
CaO (%)	0.76	63.32
MgO (%)	0.73	1.15
SO_3 (%)	–	2.10
L.O.I (%)	40.96	2.40
P_2O_5–P_2O_3	0.27	–
Na_2O	0.28	–
TiO_2	1.17	–
K_2O	2.02	–
Blaine (cm^2/gr)	–	3050
Expansion (autoclave) %	–	0.05

Table 3
Physical properties of cement.

	Compressive strength (MPa)
2 day	11.77
3 day	18.14
7 day	28.93
28 day	37.17

3.3. Untreated coal waste (UCW)

In this study, untreated coal wastes available in Anjir Tangeh coal washing plant was used. Raw coals from various mines situated in this zone was gathered for the preparation process in the coal washing plant. The plant, located in Zirab, northern Iran, produces and dumps plenty of untreated coal wastes around the plant area. The 2-hectare dump was of ten meters high and over 2 million tons weight which causes numerous environmental issues within the area due to annual rainfall. The unit weight of untreated coal wastes was 1240 kg/m^3 and their compressive strength was about 25 MPa. Fig. 3 represents gradation curves of aggregate and untreated coal waste and Table 2 also shows the chemical compound analysis of untreated coal wastes. In addition, different sizes of untreated coal waste are given in Fig. 4.

4. Experimental work

The concrete specimen mix compositions are presented in Table 4. Mix No.1 with no untreated coal wastes is considered as the control one. The rest of the mixtures contained untreated coal wastes as replacements of sand and gravel. However in all of the mixes, water/cement (W/C) ratio was kept constant. The slump test was carried out following ASTM C143 [70] standard. The test apparatus is comprised of a circular truncated cone with upper and lower diameters of 100 and 200 mm, and a height of 300 mm. The mold was filled with concrete in three layers, each of which compacted with 25 tamps. Then, the mold was lifted slowly. The amount of concrete mixture settlement under its own weight was measured as the concrete slump. Once the con-

Fig. 4. Untreated coal waste in different size.

Table 4
Concrete mixture proportion.

Mix No.	Group	UCW (%)	W/C	(Kg/m^3)				
				Cement	Water	Gravel	Sand	UCW
1	G-J-S	0	0.55	391	215	854	855	0
2		5	0.55	391	215	811.3	855	32.04
3		10	0.55	391	215	768.6	855	60.70
4		15	0.55	391	215	725.9	855	86.00
5		20	0.55	391	215	683.2	855	107.92
6		25	0.55	391	215	640.5	855	126.47
7	S-J-S	5	0.55	391	215	854	812.25	29.11
8		10	0.55	391	215	854	769.5	55.15
9		15	0.55	391	215	854	726.75	78.14
10		20	0.55	391	215	854	684	98.05
11		25	0.55	391	215	854	641.25	114.91

UCW: Untreated coal waste; G-J-S: Gravel Jig sample (coarse recycled aggregates); S-J-S: Sand Jig sample (fine recycled aggregates).

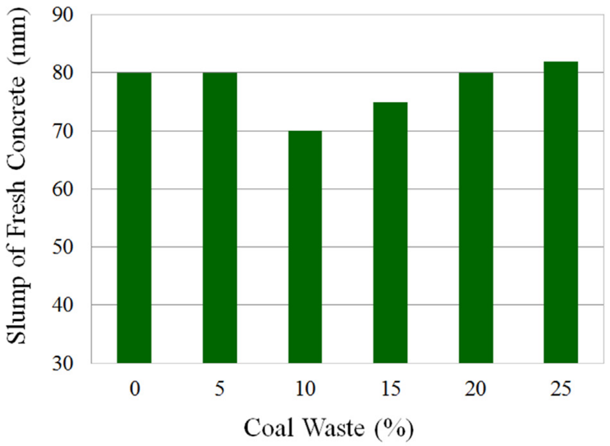
crete cubes, cylinders and prisms were cast, water tank was used to cure the specimens according to ASTM C192 [71] standard. Table 5 illustrates the experimental program.

The ASTM C39 [72] standard mandates testing of the compressive strength of cubic specimens (100 × 100 × 100 mm) at the ages of 7, 14 and 28 days. In this regard, the axial compressive load was applied to specimens through an automatic hydraulic jack until reaching ultimate strengths. The measured maximum load was then divided by the cross-sectional area to obtain the compressive strength. Water absorption of the specimens was also tested on cubes at age 28 days, based on ASTM C642 [73]. Furthermore, splitting tensile strength test was performed for cylinders (150 × 300 mm) conforming to ASTM C496 [74] such that the specimen was placed horizontally into the testing machine and the load was exerted via a loading roller along the vertical axis of specimen continuously until fracture occurred. In addition, based on ASTM C469 [75], the elastic modulus was determined in that the cylindrical specimens were placed in a special ring which included a dial gauge with the resolution of 0.002 mm. Then, load and deformation were measured while the load was approaching 40% of its maximum value. Five cycles of charge and discharge were performed in this test. The 28-day flexural strength was also measured through casting beam specimens (500 × 100 × 100 mm) in accordance with ASTM C293 [76] in a way that the specimens center was loaded via the Universal Testing Machine (UTM) up to the beam collapse.

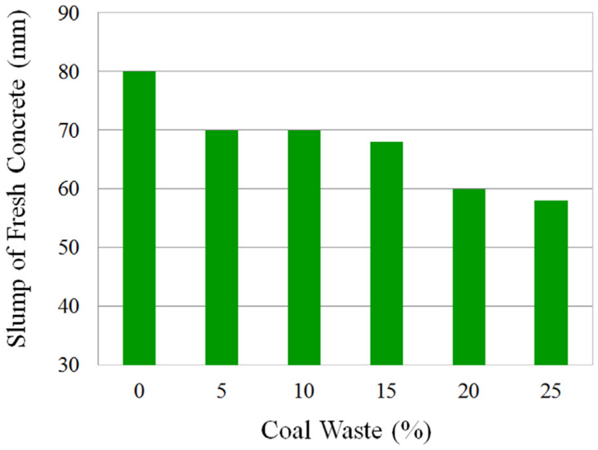
5. Results and discussion

5.1. Fresh concrete properties and dry unit weight

The results of slump test, which measures the workability of freshly made concrete and consistency of mix design, are presented in Fig. 5a and 5b respectively for different replacements of gravel and sand with untreated coal waste. Substituting sand with untreated coal waste, as compared to gravel replacement, contracts the workability and slump of concrete due to presence of high specific surface area and much finer dimensions. This can possibly be attributed to the crushed appearance and similar material of untreated coal waste to that of coarse aggregate. In this



(a) Gravel



(b) Sand

Fig. 5. Slump of specimens at different percentages of replacing aggregate by untreated coal waste a) Gravel, b) Sand.

Table 5
Experimental program.

Test	Cubic sample 100 × 100 (mm)	Cylindrical sample 150 × 300 (mm)	Beam sample 500 × 100 × 100 (mm)
Compressive strength test*	3	–	–
Splitting tensile test	–	3	–
Modulus of elasticity test	–	3	–
Flexural test	–	–	3
Dry unit weight test	2	–	–
Water absorption test	2	–	–

* Compressive strength tests were performed for cubic samples at ages of 7, 14 and 28 days.

study, the slump value for plain concrete (without untreated coal waste) is 80 mm. According to Fig. 3a, it can be seen that with the addition of coal waste for 10% of coarse aggregate by volume, slump is reduced to 70 mm. Likewise, Fig. 5b illustrates that 25% partial substitution of fine with coal waste, changes the slump from 80 mm to 58 mm, indicating a 27% reduction in slump.

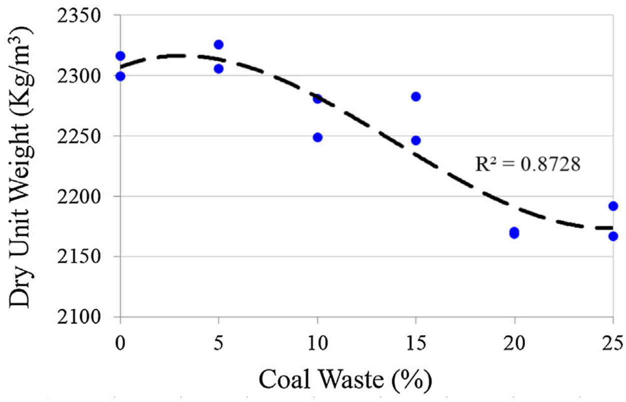
Fig. 6a and b depict variations of concrete dry unit weight against untreated coal waste content. As it is observed, the dry unit weight of specimens is decreased with increasing coal waste content. This is mainly because of the lower unit weight of untreated coal wastes as compared with the aggregates. However, the dry unit weight was discerned to increase when the aggregate replacement content was 5%. Actually, at such a low replacement amount, untreated coal wastes possibly fill the void ratios and hence rise the dry unit weight.

As demonstrated in Fig. 6, with increasing coal waste percentage, the unit weight of concrete specimens decrease compared to plain concrete (without untreated coal waste), as coal wastes are lighter than aggregates. In addition, the use of coal wastes as a substitute for concrete fines is more pronounced on reducing the specimen density. Therefore, incorporating 25% of coal waste replaced for sand with dry unit weight of approximately 2140 kg/m^3 has the greatest impact on decreasing the unit weight of concrete specimen.

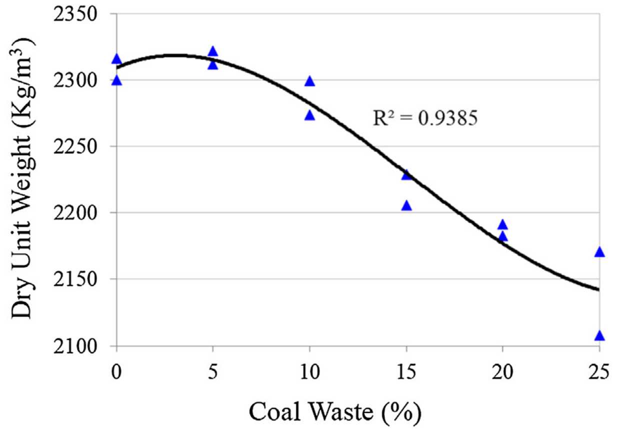
5.2. Compressive strength

Compressive strength of concrete, as one of the major factors of structural design, is certainly one of the most important mechanical properties and quality characteristics of concrete. To this end, the cubes were tested at different curing ages to examine the compressive strength, such that three specimens were prepared for each of the curing ages to obtain a better accuracy with less deviation. Fig. 7a and b show variations in concrete compressive strengths with untreated coal waste contents at different ages. Based on the research accomplishments it is generally regarded that the mechanical characteristics of cement [39,43,45,77–83,90,91,93] and concrete [22,84–87,92] are strictly connected with parameters including microstructure, density, etc. It is elaborated in the figures that with increasing curing age, the compressive strength is increased. This is possibly because the physical and chemical structure of the concrete is improved by the hydration process. It was found that 5% replacement of untreated coal waste increased the compressive strength of cubes by approximately 6%; however, no discrepancy was observed at 10% of replacement. As the amount of replacement elevated, the compressive strength was generally reduced. It is worth noting that the compressive strength of untreated coal grains were one-third of that of aggregates, which accelerate specimen fracture as the replacement content is increased. The way the paste and gravel is located can be added to the cited evidence at lower replacement contents.

In addition, the reason to compressive strength reduction in concrete containing coal waste is the porosity in such aggregates, which prompts weaker interfacial transition zone (ITZ) compared to conventional concrete (without recycled aggregate). Hence, cracking is swiftly initiated around recycled aggregates (untreated coal wastes) under compression loading, which results in the reduction of compressive strength of concrete.

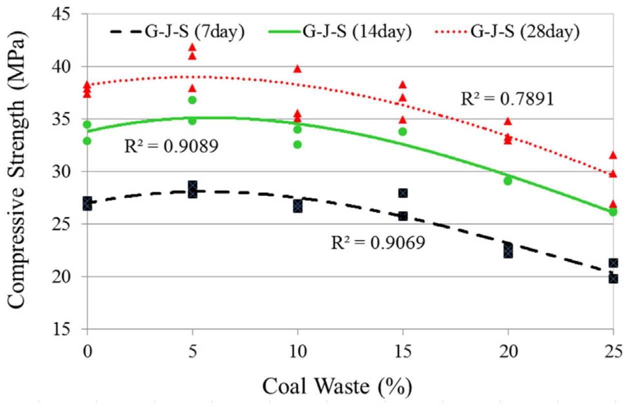


(a) Gravel

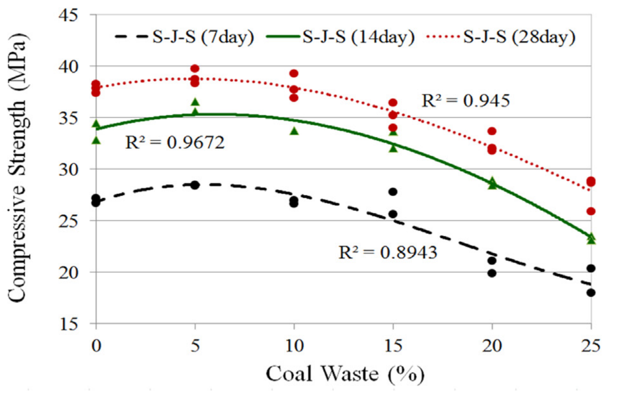


(b) Sand

Fig. 6. Dry unit weight of specimens replacing a) gravel, b) sand with untreated coal waste.

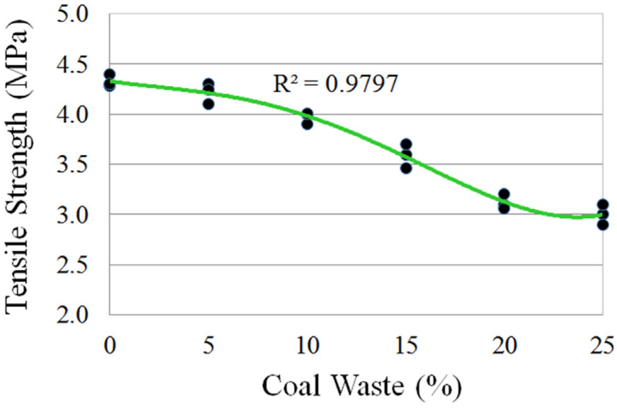


(a) Gravel

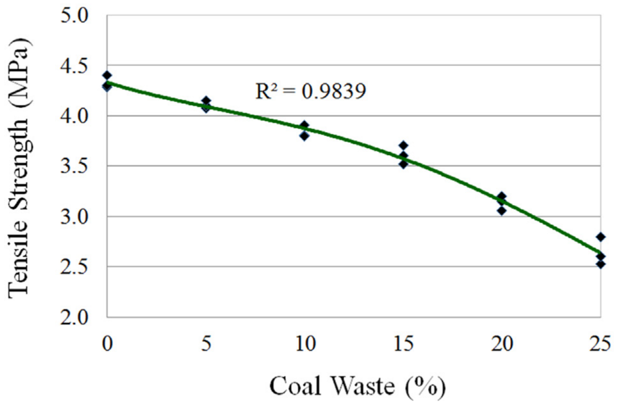


(b) Sand

Fig. 7. Compressive strength of specimens at various percentages of replacing.

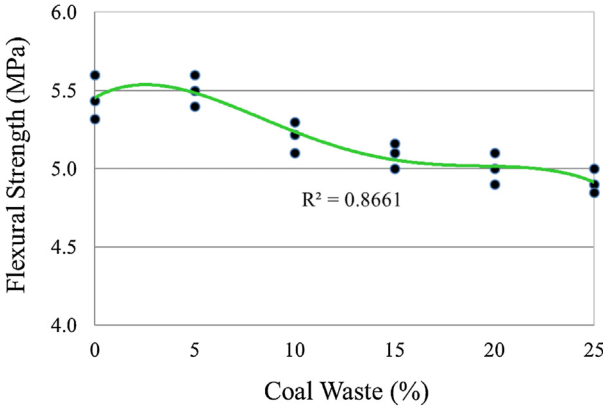


(a) Gravel

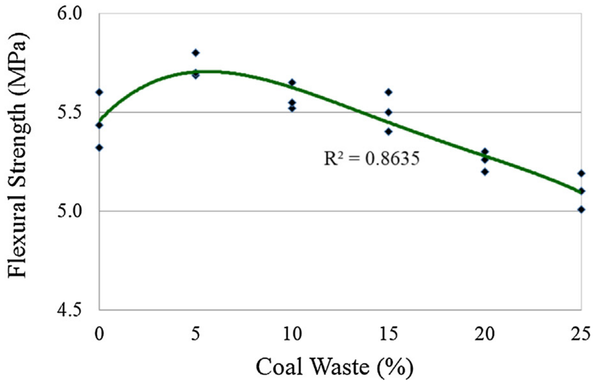


(b) Sand

Fig. 8. Splitting tensile strengths of specimens at different percentages of replacing a) gravel b) sand with untreated coal waste.



(a) Gravel

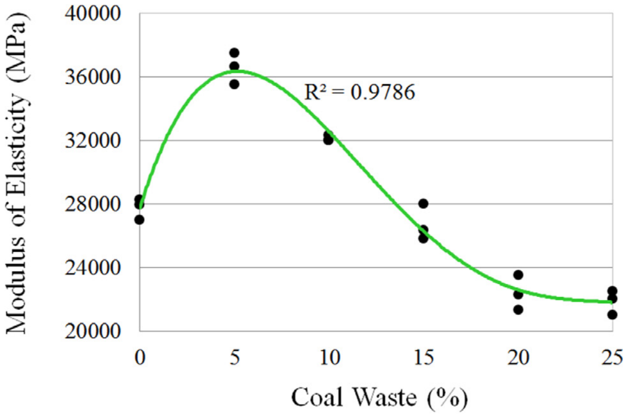


(b) Sand

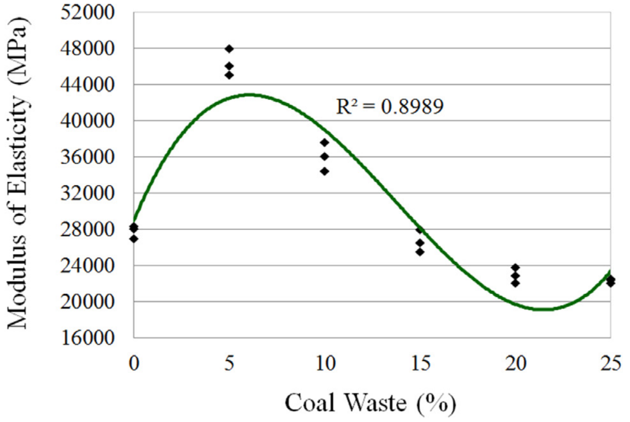
Fig. 10. Flexural strength of specimens replacing a) gravel b) sand with untreated coal waste.

Correspondingly, it is inferred from Fig. 7 that substituting coal wastes for sand by volume has a greater influence on reducing the compressive strength of concrete, as compared to gravel replacement. The reason to which is associated with the lack of bond improvement between cement paste and aggregates, and an increase in pores of cement paste. Another reason could involve the porosity of coal waste particles, which degrades the strength of

Fig. 9. Universal testing machine used in this study.

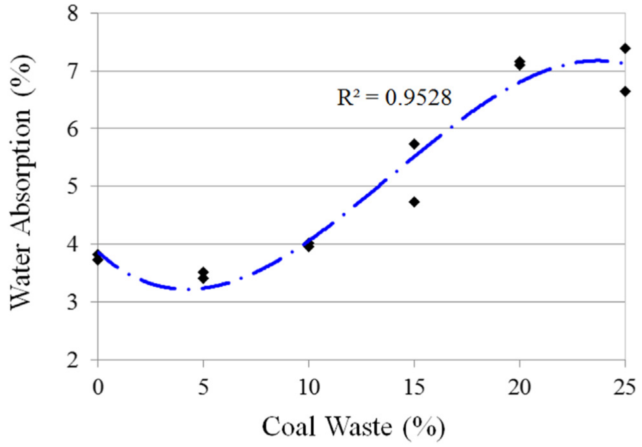


(a) Gravel

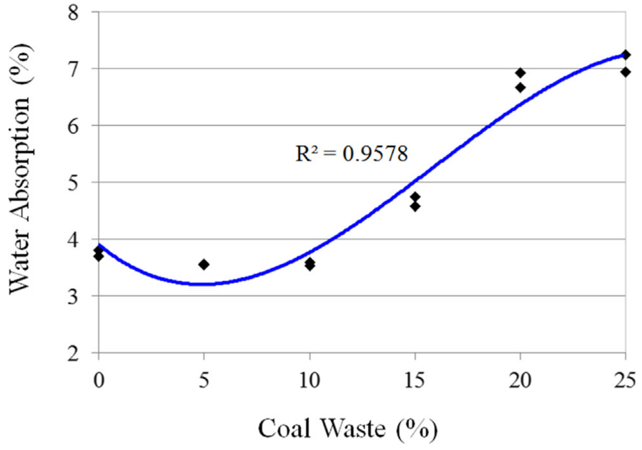


(b) Sand

Fig. 11. Modulus of elasticity of specimens at 28 days a) gravel-replaced b) sand-replaced.



(a) Gravel



(b) Sand

Fig. 12. Water absorption of a) gravel-replaced b) sand-replaced specimens.

concrete. Therefore, 5% of coal waste can be regarded as the optimal replacement percentage for coarse and fine aggregates in this study, being valid for all ages.

5.3. Splitting tensile strength

In order to evaluate the splitting tensile strength, cylinders at the age of 28 days were examined. As shown in Fig. 8a and b, tensile strength decreased as the untreated coal waste content increased.

Substituting natural gravel with coal wastes, the tensile strength of concrete is reduced such that specimens with 5, 10, 15, 20 and 25% of recycled coarse aggregates display a reduction of 2.3, 9.1, 17, 26.1 and 31.8% as to specimens without untreated coal waste. Further, the splitting tensile strength of concrete specimens mark 6.8, 11.4, 18.2, 28.4 and 37.5% decrease when respectively 5, 10, 15, 20 and 25% of coal waste substitute natural sand, compared to plain concrete.

The reason for the decrease in tensile strength of concrete containing coal waste is that recycled aggregates, specifically fine coal particles, play an isolating role among other solid ingredients of the concrete mixture. Thus, ITZ bond is weakened and the resulting stress concentration leads to faster failure of concrete in tension [88]. In this regard, the weak bond between cement paste and coal waste is the main cause of segregation between the two constituents in the course of cracks expansion and their (cracks) outstretching to the contact surface of aggregates under tensile stresses. However, Fig. 8a and b express that concrete with coarse coal grains (recycled coarse-grained concrete) features higher tensile strength than the one with fine coal grains (recycled fine-grained concrete).

5.4. Flexural strength

The flexural strength of specimens at the age of 28 days was determined by Universal Testing Machine (Fig. 9). Variations in flexural strength values of specimens with untreated coal waste contents are shown in Fig. 10a and b. Flexural strength in both sand and gravel replacement is shown in Fig. 10. According to the results of Fig. 10, flexural strength of concrete decreased with increasing coal waste percentage replaced for natural aggregates.

In gravel replacement, gain in flexural strength by 1% and a maximum reduction of 10%, are respectively related to 5 and 25% of untreated coal waste addition (see Fig. 10a). In sand replacement, however, the flexural strength increased by 6% and decreased by 7% respectively for 10 and 25% substitution of untreated coal waste (see Fig. 10b). As a consequence, it is discerned that lower replacement percentages of recycled (coal) aggregates with natural ones improved the flexural strength of concrete. Flexural strength loss in concrete specimens containing high percentages of coal can be connected with poor bonding between cement paste and coal waste, which results in weaker

ITZ in the specimens. Hence, cracks develop in specimens due to tensile load induced by bending, which is immediately followed by flexural failure of specimens.

5.5. Modulus of elasticity

The elastic modulus is imputed as a parameter of high significance in evaluating the properties of concrete material, which yields useful information on the viability of concrete to elastic deformations in the design of concrete structures.

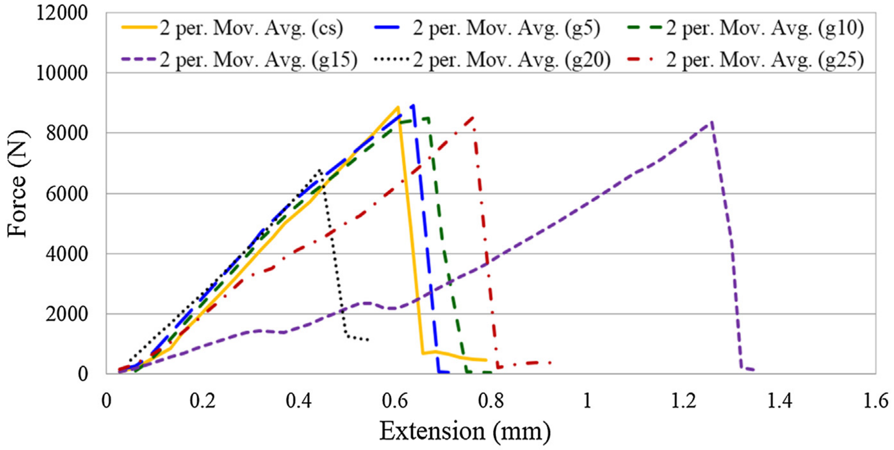
Fig. 11a and b illustrate the 28-day elastic modulus of specimens at different untreated coal waste contents. As it is seen, the elastic modulus is increased at first when the aggregate is replaced with untreated coal waste, though followed by a gradual reduction. This rate of increase at 5% of replacement is 35%. However, elastic modulus is decreased by 20% at 25% of replacement. Thereby, it is inferred that the reduction in the elastic modulus stems from the smaller elastic modulus of untreated coal wastes as compared to the aggregates. Likewise, the initial surge in elastic modulus is attributed to the interaction of paste and waste particles.

In addition, reduction in the elastic modulus of concrete containing coal wastes, as compared to its coal-free counterpart, is grounded on the poor physical structure of this recycled material with less deformation resistance as to natural aggregate. In general, the elastic modulus of concrete is considerably influenced by the shape and size of aggregate, and in particular its composition [89]. According to Fig. 11, it can be seen that applying coal waste up to 10% replacement of aggregate volume increases the amount of concrete elastic modulus, though higher percentages reduce the Young's modulus. Therefore, the highest amount of elastic modulus was obtained for the concrete specimen containing 5% of coal waste (as the optimal volume replacement for fine and coarse).

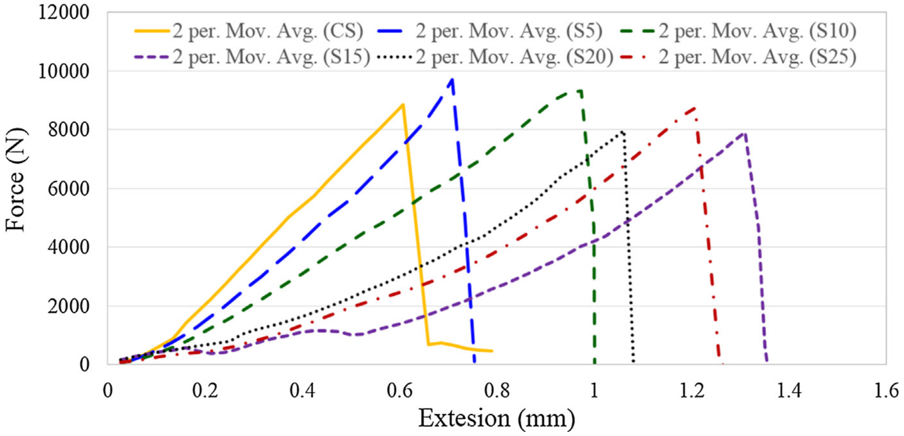
5.6. Water absorption

Water absorption is one of the main parameters of concrete durability, and water absorption percentage is a criterion to measure the pore volume or porosity of hardened concrete. Among concrete properties, water absorption is of great importance since higher permeability rates lead to lower possibility of fitting corrosion embedded in concrete.

Experimental results of water absorption percentage of concrete specimens are presented in Fig. 12. Test results (Fig. 12a and b) confirmed that the untreated coal waste replacement augmented the water absorption rate. However at 5% of replacement, untreated coal waste particles start to fill the voids within the mix and thus water absorption is tapered by approximately 8%. Therefore, in gravel and sand replacements, concrete specimens with 25% of coal waste have the highest water absorption rate, which is approximately 85%



(a) Gravel



(b) Sand

Fig. 13. Force-Extension curves of a) gravel-replaced b) sand-replaced specimens.

higher than that of reference concrete (without coal waste). In fact, adding coal wastes in lieu of natural aggregates increases the porosity of the concrete mix, thereby increasing the water absorption of hardened concrete. Another motive could possibly be the greater water absorption and porosity of coal wastes, which increases such rate in the concrete containing coal waste.

5.7. Force-Extension curves

Force-Extension curves obtained from Universal Test Machine (UTM) are shown in Fig. 13a and b. Fig. 13a signifies the maximum force tolerance value by using 5% of untreated coal wastes instead of gravel that it is about 0.89%. But, in Fig. 13b the force tolerance value increase about 6.7% by using 5% of untreated coal wastes instead of sand.

It can also be seen from the force-displacement diagram that partial volume replacement of aggregates with coal waste decreases the flexural stiffness and strength of concrete specimens. Fig. 13 depicts that concrete specimens with 15% coal waste reflect higher deflections than concrete specimens. This can be linked to the high flexibility and high energy absorption of coal, as well as its low tensile strength and the lack of proper bond between coal and cement paste which causes more deformation when loaded. Replacement of gravel and sand with coal waste resulted in the least deformation amount respectively in concrete containing 10% of coal and the one without coal.

6. Conclusions

The current paper investigated the mechanical properties of green concrete featuring different amounts of untreated coal wastes (UCW) contributed as aggregates. Herein, a number of conclusions are presented:

- The concrete unit weight displayed a decreasing trend with increasing untreated coal waste particles.
- Deformability of specimens remained unchanged as the untreated coal waste increased.
- It was noticed that 5% replacement of untreated coal waste increases the compressive strength of cubes by approximately 6%. However, no discrepancy was observed in terms of compressive strength at 10% of replacement, when compared to control specimens without untreated coal waste addition. As the replacement content elevated (exceeding 10%), the compressive strength was reduced.
- By increasing untreated coal waste content, the specimens' tensile strength decreased. However, at 5% content of waste material, tensile strength was the same as to that of control specimens without waste particles.
- Enhancement in the elastic modulus of specimens was witnessed as 10% of aggregates were replaced with untreated coal wastes. A reduction was then followed as the amount of untreated coal waste content increased. However, maximum elastic modulus was experienced at 5% of replacement.
- At 5% of replacement, water absorption was tapered by approximately 8%, signifying a favorable approach.
- Based on the outcomes, the overall properties of concrete mixture were enhanced when replacing 5% of aggregates with untreated coal wastes.
- In the end, it is obvious that recycling untreated coal waste particles can be benefited instead of concrete aggregates in the civil engineering practices. Moreover, selecting an appropriate amount of replacement, one can obtain the property improvement of concrete, as well as an environmental solution to reducing coal wastes, so as to meet the objectives of sustainable development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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