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Review Research

A REVIEW OF STEEL SLAG AS A SUBSTITUTE FOR NATURAL AGGREGATE APPLIED TO CONCRETE COLUMNS

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Abstract: There are severe ecological imbalances from both carbon emissions and sand mining. Steel slag can be used as an aggregate in concrete to enhance the environment and conserve natural resources because of the impact of depleting resources. The paper's main aim is to investigate the appropriateness of steel slag as an aggregate substitute and determine its impact on the behavior and durability properties of columns subjected to various circumstances and loads. After discussing slag and its properties, its effects on plain concrete were reviewed, followed by its effects on concrete columns. Previous studies indicate that columns made with steel slag aggregate concrete have comparable initial stiffness, strength, and flexibility as regular concrete. For columns with fine steel slag aggregates, the conventional section design approach can be used as an option for the design method. The European standard for stub columns filled with steel slag aggregate concrete under compression is more accurate than the American standard, which is circumspect.

Keywords: *Coarse aggregates; electric arc furnace slag; fine aggregates; induction furnace slag; reinforced concrete; slag; Stub columns*

1. Introduction

Environmental rules in several nations limit industrial waste disposal and reuse [1-2]. In the building industry, the demand for materials is rising, and conventional materials can't keep up. Instead of utilizing natural resources, this problem can be solved by reusing waste materials such as steel slag (SS). It can reduce production material costs [3].

Steel slag is a by-product of steel scrap, pig iron, or both [4-6]. Steel slag production occurs in electric arc furnaces, induction furnaces, ladle furnaces, and basic oxygen furnaces [7-9]. Steel slag contaminates the environment [10]. Therefore, environmental protection requires studying SS utilizes [11-13]. In contrast, local projects utilized a lot of traditional aggregates. Meanwhile, over-mining aggregate causes natural vegetation damage and soil erosion [14]. Therefore, extensively using slag promotes sustainable development. Crushed steel slag can be utilized in concrete as both fine and coarse aggregate[15,16]. Early test data on slag aggregate mechanical and physical properties, crushing value, sturdiness, structural stability, and shock strength revealed that the aggregate demonstrated met standard specifications. According to mechanical testing, slag aggregate generally has better strength and ductility than regular aggregate and can be used as a concrete aggregate [16-18]. The key disadvantages of SS aggregate include its unfavorable reactivity with concrete

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components, as well as its expansive properties [19].

This paper summarizes findings on the usage of SS aggregates on column behavior. The first section explains the concept, type, and attributes of SS aggregate from previous studies. The second objective is to establish a foundation for future research on the utilization of SS aggregate in civil engineering applications. Before considering the influence of SS on the mechanical and durability properties of concrete columns, the effect of SS on concrete was evaluated.

2. Steel Slag (SS)

2.1. General

The steel industry produces non-metallic SS as a co-product of steel. Steel slag has a honeycomb-like structure and a significant degree of porosity shown in Fig. 1. Refining blast furnace-produced hot metal into steel creates SS [6,20]. Slag was historically utilized for road construction and as a filler material. Recently, slag has been utilized as a cement additive, landfill cover, and building material [21-23]. Steel slag was primarily composed of CaO, SiO_2, Fe_2O_3, Al_2O_3, and MgO [24,25]. The Steel slag chemical composition varies by the type of furnace, steel grade, and pretreatment method. Source-to-source chemical composition differences cause this variation [2]. Due to the low amount of reactive calcium silicate, it has poor cementing characteristics [26]. Steel slag silicate phases are less active than cement silicate phases [27]. Therefore, the excessive substitution of cement with SS diminishes the mechanical properties and durability of concrete [10]. Steel slag includes significant quantities of CaO and MgO, which cause immediate and long-term expansions. The delayed hydration of free calcium and magnesium oxides causes the expansion of cement-based materials. Volume stability is a building criterion for using SS as a construction material [28, 29]. Reducing free oxides before utilizing SS in concrete treatment is generally recommended. Slag is aged, weathered, and cured, employing steam or an autoclave to decrease expansion problem content[30,31].

This issue can also be solved by storing SS in stockpiles for six months until using it. Untreated steel slag can be employed for unbound aggregate applications[32-34].

Figure 1. Surface form of the slag.

2.2. Steel slag aggregate

Traditional building materials can't keep up with the industry's growing demand. Instead of using natural aggregate, waste materials such as fly ash, rubber, glass, construction waste, and different kinds of slag, such as steel, lead, copper slag, and can be reused. [2,23] The environmental advantages of utilizing SS aggregates in place of natural aggregates are substantial. The strength, dimensional stability, workability, and durability of concrete are significantly impacted by the aggregates. [35]. Steel slag aggregates can replace a fraction or all of the volume of aggregates in concrete. Slowly cooled slags are appropriate to be utilized as aggregate in concrete due to their better characteristics. Maintaining volume and achieving high density are the goals of this treatment. And yet, the quality of concrete produced with a certain percentage of vitreous components is unaltered [36]. Adding SS aggregate to concrete can enhance its compressive strength by up to 20% [37]. Steel slag aggregate has a higher angularity than natural aggregate, contributing to better mechanical interlock with cement paste. It has also been found that SS concrete's compressive strength might be equivalent to or lower than standard concrete. Because of its porous nature, large SS can easily break and decrease the strength of concrete[38]. The quality of SS aggregate also influences concrete strength, and the influence of many parameters (such as cooling process and chemical composition) on SS aggregate quality should be taken into account [9, 39].

3. Review of the effect of steel slag aggregate on concrete

Akinmusuru et al. 1991 [40] studied the SS effect on concrete strength. The slag was employed twice: once as fine aggregate (FS) and once as coarse aggregate (CS). Cast concrete cubes (150 mm on each side) were immersed in water for 7, 14, 21, and 28 days to cure. The mix ratios were 1: 1½: 3 and 1: 2: 4, with water/cement ratios ranging from 0.52 to 0.55. The results indicated that when the sand was replaced by slag, the steel slag aggregate concrete's (SSAC) crushing strength was higher than conventional concrete. The CS concrete was stronger than regular concrete. When compared to CS concrete, FS concrete is stronger. This is due to sand-sized slag particles having a greater gross surface area accessible for reacting with the cement than gravel-sized slag particles. Concrete cubes absorbed more water than FS concrete. After 21 days in water, all mixtures retained roughly the same absorption rate.

Montgomery et al. 1992 [41] investigated the effect of replacing coarse aggregates with SS on the fracture properties of concrete. The concrete's fracture-related properties were quantified by measuring its brittleness and fracture toughness. Prism specimens of 100 mm x 100 mm x 300 mm were subjected to longitudinal compressive testing to establish the SSAC's brittleness. Sixteen mixes were developed with variable water-to-cement ratios, slag percentages, and cement percentages. Target values were established for cement content (260, 310, 370, and 420 kg/m3), slag content (1360, 1400, 1440, and 1480 kg/m3), and water/cement ratio (0.48, 0.56, 0.64, and 0.71). The results showed that steel slag improved compressive, tensile, flexural, and modulus of elasticity properties while decreasing brittleness and improving fracture toughness. SSAC has a much lower brittleness index than similar concretes made with limestone aggregate, and this trend continues as compressive strength is increased.

Abdulaziz et al. 1997[42] investigated the possibility of using EAFS as coarse aggregate in concrete. Along with the slag, crushed wadi gravel was used for comparison. The shrinkage and mechanical properties of SSAC and gravel concrete were tested under different curing conditions and with two W/C values of 0.42 and 0.62. The compression was tested at 3, 7, 28, 90, and 210 days. Flexural and splitting tensile strengths, drying shrinkage and modulus of elasticity were tested at 28 days. The results showed that slag concrete has compressive and flexural strengths comparable to or even higher than gravel concrete. Additionally, its splitting tensile strength and modulus of elasticity were higher, and its drying shrinkage was lower.

Mohammed et al. 2009 [43] investigated the effect of substituting SS slag as coarse aggregate in concrete modification. Concrete mixtures with partial SS replacement (0, 25, 50, and 60%) by cement wt were utilized. Cubic density, water absorption, and compressive strength They investigated. The results indicated that the optimal compressive strength of cubic samples was for 60% SS replacement, which improved 59% in 7 days and 71% in 28 days. After 7 and 28 days, increasing slag content increased concrete density and compressive strength while decreasing water absorption. These results indicate the importance of utilizing SS in the modification of concrete properties.

AL-Ameer and Matter. 2011 [44] investigated the utilization of SS in concrete as a partial replacement for gravel. The study included the impact of SS on concrete quality under various conditions, such as slump, compressive strength, tensile strength, and shrinkage at (28 and 90) days. The test investigated the impact of substituting slag in the following proportions mix design: (0, 30, and 60%). The result demonstrates a decrease in workability and shrinkage. For 60 % SS, the compressive strength increased by 15% after 90 days, while for 30 % and 60% SS, the compressive strength increased slightly after 28 days. About (30% and 10%) of the tensile strength was increased after 28 days of slag replacement by 60% and 30%, respectively.

Jassem et al. 2011[45] investigated the utilization of slag by replacing sand with slag by weight in 10% increments (from 0% to 40% of the weight of the sand). with added superplasticizer (melment L10) to the mixture at a rate of 5.5% of the cement's weight. The results showed improvements in the characteristics of concrete when 10% and 20% slag were used instead of sand: workability, initial surface absorption, total absorption, and porosity relative to the reference mix improved. However, adding 30% or 40% resulted in low concrete workability and increased initial surface absorption as total absorption and porosity.

John and John 2013[46] investigated SS as an alternative to fine aggregate. The slump and compressive strength properties of mortar and concrete prepared with partial replacement of fine aggregate with SS were examined in this study. Induction furnace slag (IFS) is utilized as a replacement for fine aggregate by weight in increments of 10% (ranging from 20% to 60%). Slag is added to the mixture in weight increments of 10% (from 20% to 60%) to replace fine aggregate. Tests of the compressive strength of concrete and mortar showed that fine aggregate replacement with 30% IFS outperformed the control mix. A mortar mix with an IFS greater than 30% has a poorer compressive strength than a control mortar mix that contains no slag. According to the results, concrete containing IFS by up to 30% has a larger slump than any other mix. Consequently, slag particles can be utilized as a fine aggregate in concrete. A maximum of 30% of the fine slag can be substituted.

Kim et al. 2013[47] investigated the effect of electric arc furnace slag (EAFS) slag in spirally confined concrete. Twelve unconfined and 48 laterally reinforced cylindrical specimens were cast and tested under concentric vertical load. The dimensions of cylindrical specimens were 150 mm in diameter and 300 mm in height. Variables include aggregate type, reinforcement yield strength, and spiral steel ratio. Based on experimental and analytical results, SS aggregate specimens demonstrated an enhanced strength comparable to that of natural aggregate, while ductility was superior to that of natural aggregate and increased with the increasing yield strength and steel ratio of spirals. As EAFS aggregate ductility increases, peak strain prediction methods become less accurate.

Yeole et al. 2018[48] studied the influence of substituting fine aggregates with SS on concrete strength. Five concrete mixtures were employed with SS replacement ratios of 0%, 5%, 25%, 30%, and 35% by wt. In hardened concrete cubes, compressive strength was measured after 7, 14, and 28 days of curing, while slump was measured on fresh concrete. The slump value decreases with SS. It drops from 80 mm at 0% SS to 60 mm at 35% SS. Based on compressive strength data, 25% replacement of fine aggregate with SS is the optimal percentage of replacement for concrete that enhances its compressive strength. The utilization of SS as fine aggregate improves the concrete's compressive strength. The use of SS in concrete solves an environmental issue associated with the steel industry while preventing the loss of natural sand.

Ahmad et al .2018 [49] investigated the effects of incorporating SS slag with recycled aggregate in concrete. Three goal strengths, 17.23, 20.6, and 24.1 MPa, for each target strength, substituting recycled coarse aggregate with IFS in increments of 25%, ranging from 0 to 100% by wt. The samples were examined for compressive and modulus of elasticity, tensile strength, chloride penetration, and porosity. The outcomes revealed that the splitting tensile strength and compressive strength increased while porosity and absorption decreased when IFS was substituted by up to 50%. The modulus of elasticity improved when comparing induction furnace SS replacement ratios to 100% recycled aggregate concrete. In light of these findings, it is determined that 50% of recycled aggregate can be substituted by induction furnace SS, which results in concrete with higher mechanical and durability attributes.

Nguyen et al. 2020 [50] studied the effect of replacing coarse aggregate with SS on concrete's compressive characteristics. Under compression, three types of SS concrete were tested, with ratios of 1.76, 2.21, and 2.36 for cement to water, respectively, and coarse aggregates to fine aggregates ratio of 1.98. The compressive strength was measured after 7, 28, and 360 days. At 28 days, the modulus of elasticity and Poisson's ratio of the steel SSAC were measured. According to the findings, the compressive strength of SSAC at 7 and 28 days was roughly equivalent to 55–66% and 69–73% of the compressive strength of SSAC at one year. Also, the relationship between compressive strength and the cement-to-water ratio was almost within the bounds of traditional concrete. The Poisson's ratios and elasticity module for SS concrete were comparable to conventional concrete. As the ratio of cement to water increased, the value of the slump decreased.

Gang et al. 2021[51] examined the addition of SS as a coarse aggregate in concrete under uniaxial compression. Six groups of 100-mm cube specimens and 100*100*300-mm prism specimens were utilized. Concrete mixtures were employed with SS replacement ratios of 0%, 10%, 30%, 50%, 70%, and 100%. The physical and chemical properties of SS aggregate and its stability were tested. The results show that the free calcium oxide and water immersion expansion rate of SS are appropriate for use as concrete aggregate. Brittle properties are more visible in SS coarse aggregate concrete than in conventional concrete; the prism compressive strength to cube compressive strength ratio in SS concrete is 0.83-0.9.

4. Review of the Impact of SS Aggregate on Concrete Column

Kim et al. 2014[52] evaluated the flexural performance of reinforced concrete (RC) columns using different types of natural aggregate. (AN), coarse EAFS aggregate (CS), fine EAFS aggregates (AS)) and axial loads. Six reinforced concrete (RC) columns were tested. The specimens were to have a cross-section of 250 × 250 mm and a length of 1,500 mm within the test area. The columns underwent flexure testing and were exposed to reversed cyclic antisymmetric moments. According to the results, slag aggregate specimens have more ductility capacity than natural aggregate specimens. The displacement ductility index was higher for EAFS. The flexural strength of EAFS aggregates was comparable to that of natural aggregates, regardless of axial force. The course EAFS aggregate series specimens had similar post-peak behavior to the naturally aggregated AN series specimen. However, the specimens' ductility was enhanced with the fine SS aggregate. Comparing experimental and analytical results reveals that the specimen with EAFS aggregates safely meets the ACI 318-11 code [53].

Yu et al .2015 [54] studied the axial compression of steel-tube (CFST) columns filled with concrete. Each of the five concrete mixes was made using a different type of aggregate: limestone aggregate, coarse and fine steel slag, coarse steel slag aggregate, steel slag and waste glass aggregate, and lightweight aggregate. Six circular and seven square CFST stub columns were tested. The experimental results indicate that SS or waste glass can substitute part or all of the concrete aggregates. The novel composite columns have similar and, in some cases, better structural behaviors than standard CFST columns. The concrete CFSSC coarse and fine SS, SSGC steel slag, and glass concrete had higher strengths than the control limestone mix. However, concrete CSSC coarse steel slag aggregates had a 3.3% lower strength than the control mix. Due to its porous texture. Forecasts based on finite element analysis agree with test results. The strength, initial stiffness, and ductility of the CFST columns containing SS are comparable to those of regular concrete.

Yu et al. 2016 [55] tested axial compression on CFST stub columns filled with five concrete mixes. SS, limestone, lightweight aggregate, and waste glass aggregates were utilized to make concrete mixes. Sixteen circulars (177.5 × 540 × 3 mm) and seven (179 × 540 × 4 mm) squares were evaluated. The aggregate types revealed no discernible effect on failure mode compared to the control mix (limestone aggregate). Due to the enhanced interlocking, fine SS concrete was stronger than the control mix. Substituting waste glass for coarse aggregate reduces mix strength. Steel-slag CFST columns have a higher strength index due to the hydration of free lime in SS, which increases concrete volume. Since the steel tube limits concrete's volume expansion, it modifies the microstructure and increases confinement. Due to better concrete confinement, circular specimens are more ductile. Eurocode 4 [56] reasonably predicts CFST's ultimate strength.

Yu et al. 2016 [57] tested the compressive strength and fire resistance of concrete columns constructed using SS and waste glass as coarse aggregates. Also tested were limestone aggregate and lightweight aggregate concrete. Slump, density, elasticity, compressive strength, and flexural strength were utilized to evaluate concrete material properties. Five plain concrete columns with a 250 mm diameter and an 800 mm height were tested for fire performance utilizing different aggregates. The specimen was axially crushed. The furnace was heated to 800 °C gradually. The temperature held until the column failed. The results show that replacing coarse or fine gravel with SS or waste glass is possible. Concrete's mechanical properties can be enhanced by using coarse SS aggregate, however, using low-quality slag could be harmful. When comparing SS concrete to limestone aggregate concrete, it had comparable or greater compressive strength, flexural strength, and modulus of elasticity. Replacing coarse aggregate with up to 17.5% waste glass had little effect on the concrete's mechanical characteristics. Because of their thermal and/or mechanical qualities, SS and waste glass enhance the fire resistance of concrete.

Jiao et al. [58] investigated test data acquired from 12 columns (200×200×1600 mm) made of fine SSAC and subjected to horizontal low cyclic loading. There were two variables used: axially compressive force and stirrup content. Fine SS concrete with 55.9MPa (C55) and 61.6MPa (C60) strength grades were mixed. Each strength grade has two reinforcing ratios and three stirrup forms. 0.3 and 0.5 test axial pressure ratios. The results indicated that the section-bearing capacity of SSAC columns was comparable to regular concrete. Due to the enhancement in compression strength, the actual measured horizontal force value increased when fine SS aggregate was utilized. However, the indicated ductility performance of columns with a strength value of 61.6 MPa was lower than at 55.9 MPa. For conventional concrete columns, the regular section design method can be utilized for fine SSAC.

Lee et al. 2018 [59] investigated the structural properties of RC columns made with SS fine and coarse aggregates. The axial force ratio of the column section was between 20% and 30%. The amount of EAFS aggregates (0 %, 48%, and 100% of total aggregate) were the variables. Six columns with a 250 x 250 mm cross-section, a 1500 mm height, and a 3.0 shear span-to-depth ratio were tested under static loading. The investigation showed that RC columns constructed from EAFS particles exhibited improved ductile capacity after reaching ultimate strength. 1.5–2.5 times as ductile capacity as natural aggregate RC columns. In addition, the former had substantially less crushed up to the limit state at the column ends. Column specimens built with EAFS aggregates demonstrated a displacement equal to or more than natural aggregate specimens. However, the first transverse strain was half of the second. EAFS-made RC columns had shorter plastic hinges than natural aggregate columns.

Yu et al .2020 [60] evaluated the mechanical behavior of fine SSAC-filled steel tubular columns subjected to axial and eccentric compression tests. There are twelve 500-mm-long, 140-mm-outer diameter steel tube columns. Different tube thicknesses (2.08, 3.63, and 4.22), SSAC expansion rates (-3.5×10^{-4} and 2.8×10^{-4}), and eccentricities (0, 20, 40, and 60 mm) are utilized. The experimental results show that under axial and eccentric compression, shear and bending deformation dominates specimen failures, respectively. When the eccentricity and diameter–thickness ratio increase, the ultimate bearing capacity of the stub columns diminishes and stiffness deterioration is exacerbated. The increasing expansion rate improves the IRLC incremental range of the load capacity. Increasing the SSAC expansion rate increases the specimens' incremental load capacity and axial and circumferential strains. For forecasting stub column compression resistance, Euro code 4 (2004)[56] is more accurate than the American standard ANSI/AISC 360–16 (2016)[61], which was conservative.

Yu et al.2020 [62] investigated bond-slip damage in steel tubular columns filled with SSAC under axial compressive load. Eight 500-mm-long, 140-mm-outer-diameter CFST columns were utilized. Six bond-slip damaged specimens and two undamaged specimens with varying diameter-thickness ratios (2.08, 3.63, and 4.22) and expansion ratios (-3.5×10^{-4} and 2.8×10^{-4}) were tested. According to the test, axially loaded bond-slip damaged specimens fail due to outward deformation. The ultimate capacity is affected little by bond-slip damage. The expansion ratio has little effect on longitudinal displacement. Increasing the steel slag aggregate concrete (SSAC) expansion ratio within an acceptable range can improve the ultimate bearing capacity. The stiffness degeneration ratio reduces with a higher expansion ratio. That's because steel tube limits SSAC microcracks. As the expansion ratio increases, axial and circumferential strains increase. In addition, the accuracy of existing CFST design guidelines for estimating bond-slip specimen strength was tested by American specification ANSI/AISC 360-16 [61] and European specification Eurocode 4. The comparisons show Eurocode 4 (2004) [56] provides the most consistent findings for bond-slip damaged specimens.

Yu et al. 2020 [63] examined the axial compressive behavior of composite columns with SS substituting fine aggregate in concrete-filled steel tube columns of various cross-sections. Under axial compression, cross-sectioned and hollow tubular specimens are tested. First, sand was substituted by SS in weight increments of 10% (range from 0% to 50% wt). Based on 12cylinder split tensile 150 × 300 and 12cube compression 150×150 × 150 test values, 30% is the optimum amount of SS to replace fine aggregate with. Second, 8 column specimens were examined for axial compressive load utilizing 30% SS as replacement sand. Two of each style of the column: a circular column with a dimension of 150 × 500, a hollow circular column (Outer dia)150 × 500 (Inner dia) 80 × 500, a square column 150 × 150 × 150, a hollow square column (Outer) 150×150×500 (Inner) 80×80×500. The study analyzed square and circular column failure modes under axial compressive force. The hollow square column bears the most load of the three varieties. According to the study, concrete gains strength when SS is added.

Vivek et al.2021[64] evaluated the effect of SS as a partial replacement for fine aggregate on the axial compressive behavior of CFST columns. There are four columns: two with heads and two without. The steel slag concrete has similar properties to natural aggregate concrete and does not pose any complications during the process. Properties such as freeze-thaw resistance and durability improved. The durability of the mix is increased by 1.1-1.3 times when SS is employed, depending on the ratio. The concrete characteristics do not change much when the SS ratio is increased to 70%.

Fang et al. 2021[65] investigated the mechanical performance of SSAC-filled steel tubular columns. Six axially loaded short columns, each 500 mm long and 140 mm in diameter, are constructed of three types of seamless steel tubes with thicknesses of 2.08, 3.63, and 4.22 mm. In addition to water, the SSC contained graded gravel and SS. For parametric analyses, a verified finite element (FE) model for ASSIST short columns is utilized. The steel slag concrete (SSC) expansion rate can be increased to increase the load capacity incremental range. Larger columns have lower ultimate load capacity and displacement. Expanding the SSC's expansion rate can increase the load capacity's incremental range. As the diameter-to-thickness ratio grows, the columns' ultimate load capacity and displacement diminish.

5. Conclusions

From the previous review of experimental studies of concrete specimens and columns, the following conclusions can be inferred:

Slag can be used to replace fine or coarse aggregate, and the EAFS has the substitute type of steel slag for concrete column aggregate. The best mechanical properties are obtained by replacing SS with fine aggregate at a rate of 25%–50% and coarse aggregate at a rate of 30–60%.

Coarse steel slag aggregate can improve concrete's mechanical properties, while low-quality slag may decrease them. Steel slag enhances mixture durability. The columns that contain SS aggregates satisfy the criteria of the building codes. Regardless of axial force, SS aggregate columns had a similar flexural strength as regular concrete columns. However, under reversed-cyclic load, the columns SSAC demonstrated a performance improvement compared to the regular concrete columns. The columns CFST filled with SSAC have a higher strength index and a modified microstructure.

Using slag as an aggregate has positive short-term results; however, more investigation is needed to determine the long-term effects. However, further research into the slag's resistance and durability is necessary before recommending it for use in concrete columns.

Abbreviations

A list of symbols should be inserted before the references if such a list is needed. Sort in alphabetical order.

CFST	Concrete-filled steel tube
EAFS	Electric arc furnace slag
IFS	Induction furnace slag
RC	Reinforced concrete
SS	Steel slag
SSAC	Steel slag aggregate concrete

Conflict of interest

The authors declare that the publication of this article causes no conflict of interest.

Author Contribution Statement

Author Zahraa H. Ali drafted the article and collected the data with the interpretation of it.

Author Nibras N. Abdul-Hameed: proposed the research problem and supervised the findings of this work.

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