

PERFORMANCE OF ZERO-SLUMP CONCRETE MADE WITH RECYCLED CONCRETE AGGREGATE

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Abstract

Concrete with no slump that is typically used for prefabrication is known as zero slump concrete (ZSC). ZSC is sensitive to mixture proportion. Since coarse aggregate makes up the majority of the concrete volume, recycling concrete aggregates will be a great choice for reducing the amount of concrete waste. Therefore, the purpose of this paper is to analyze the impact of using coarse recycled concrete aggregate (RCA) in ZSC properties. Five mixes were manufactured, each with a different percentage of coarse RCA (0%, 25%, 50%, 75%, and 100%). Compressive strength, flexural strength, ultrasonic pulse velocity (UPV), dry bulk density, and water absorption of recycled aggregate ZSC were conducted at 7, 28 and 90 days. Experiments revealed that the inclusion of coarse RCA in ZSC degraded the quality of manufactured concrete. At 90 days, in comparison to the control mix, the minor drop was at 25% coarse RCA incorporation, which resulted in a 6.2%, 4.1%, 2%, and 2.4% drop in compressive strength, flexural strength, UPV, and dry bulk density, respectively, while there was a 24.4% increase in water absorption. The highest drop of recycled aggregate ZSC at 100% incorporation resulted in a 41.7%, 19.1%, 8.6%, and 7.6% drop in compressive strength, flexural strength, UPV, and dry bulk density, respectively, while there was a 158.8% increase in water absorption.

Keywords:

Concrete;
Zero slump concrete;
Recycled aggregate;
Mechanical performance;
Water absorption.

1 Introduction

Zero-slump concrete (ZSC) appeared in the middle of the eighteenth century as a result of the idea that using less water in concrete would produce better results [1, 2]. The concept had been extended, and ZSC was frequently utilized up until the American Concrete Institute published a guide for choosing its proportions [3]. ZSC, often referred to as dry cast concrete, is described as concrete that has a slump in the range of 0 to 25 mm [3]. In the applications, all ZSC have low compressive strength qualities (20–30 MPa), while some high-strength ZSC (70 MPa) were assessed for use in non-structural elements [2]. This concrete has applications in the precast and compacted concrete industries, where trapped air is removed using vibro press machines or roller compactors [4]. Therefore, ZSC is well known for two significant typical applications, in particular prefabricated concrete and roller-compacted concrete [1]. Precast concrete is frequently manufactured in a factory or on site and can take the form of liquid pipes, some types of blocks, and parts for structures and bridges [4].

Some researchers [4, 5] investigated the early-age compressive strength of ZSC in the presence of binders or pozzolanic materials (fly ash, quartz flour, and metakaolin) to ascertain the appropriate replacement percentages, i.e., those that improve compressive strength and enhance the consistency of fresh concrete. Najimi et al. [1] conducted a complete experimental analysis on 14 and 8 different mixes designed using ACI and dense packing methods, respectively, to analyze the durability features and determine the most appropriate procedures for mixture design and manufacture of ZSC. Results showed that with the use of siliceous filler and silica fume, the dense packing technique demonstrated relatively adequate performance; nonetheless, it displayed a lower level of strength in contrast to the ACI-designed combinations.

The building sector has a significant negative impact on the environment due to the raw material consumption, greenhouse gas emissions, and waste production that occur during the phases of building,

maintaining, repairing, and disposing of structures and infrastructure [6]. Concrete is the most widely used building material in the world. Aside from water, concrete is consumed more than any other material per person, with an estimated yearly use of close to 30 billion tons, and demand is growing [7]. This increasing demand for concrete has raised the utilization of natural aggregates (NA), which account for roughly 70% of the total volume of concrete [6]. NA is an essential component in the manufacturing of concrete. Finding alternative NA is crucial because there aren't many natural resources available for producing aggregate [8]. Building and demolition debris represent a sizable portion of solid waste in the majority of countries worldwide. They are frequently and inefficiently disposed of in landfills at a high cost, which causes landfill space to be depleted [8]. According to estimates, the world produces between 2.5 and 3.5 billion tons of building and demolition debris, and this tendency is continuing to expand [9]. Therefore, the societal sensibility for environmental conservation has remarkably increased in recent years, so most studies have focused on the creation of new, more environmentally friendly binders, modern manufacturing techniques, and the use of recycled materials and fillers [6]. Globally, a sizable amount of recycled concrete aggregate (RCA) is produced by the building of new structures, the destruction of old ones, rehabilitation, incidents of nature, and armed conflicts [8]. Over the past two decades, RCA, which is made from building and demolition debris, has been regarded as the replacement for NA in structural concrete [8]. Utilizing RCA is becoming more significant in the construction sector as a promising strategy for reducing the environmental impact of the building materials used in construction [10]. Compared to NA, RCA has a lower density, more water absorption, and lesser abrasion resistance [10].

The impact of adding RCA to concrete has been the subject of a sizable number of research papers. Harish et al. [10] used coarse RCA in place of coarse NA in concrete in amounts of 0%, 25%, 50%, 75%, and 100%. Results showed that fundamental strengths gradually decreased as the coarse RCA percentage increased, and for construction projects, the inclusion of 50% coarse RCA in the mixture may be practical. Attri et al. [11] manufactured concrete paver blocks by replacing (0%, 15%, 30%, 45%, 60%, and 75%) coarse NA with coarse RCA and found that the properties of concrete paver blocks minimized with increasing coarse RCA replacement, and 45% replacement of coarse RCA could meet strength requirements. Kumar et al. [12] used coarse RCA with a maximum diameter of 10 mm in ZSC to produce grade paver blocks by replacing (0%, 15%, 30%, 45%, 60%, and 75%) NA and noticed that the mechanical and durability properties dropped as the RCA percentage increased.

The performance of ZSC made with recycled concrete aggregates (diameter 5 to 19 mm) is examined in this study using an experimental methodology at various replacement levels for coarse RCA (0%, 25%, 50%, 75%, and 100%). To assess the manufactured concrete, tests on its compressive strength, flexural strength, ultrasonic pulse velocity, dry bulk density, and water absorption were conducted. The findings of the current study could guide or assist connected parties in determining the appropriate use of coarse RCA in ZSC production.

2 Experimental program

2.1 Materials

In this study, ordinary Portland cement that meets ASTM C150 [13] was used. Table 1 lists both the chemical and physical characteristics of the cement components.

Table 1: Chemical and physical characteristics of the cement components.

Chemical Characteristics	Results [%]	ASTM C150 limitations
CaO	62.33	.....
SiO ₂	20.5	.....
Al ₂ O ₃	4.11	.....
Fe ₂ O ₃	3.01	.....
SO ₃	1.99	≤ 3 if C3A ≤ 8
MgO	3.04	≤ 6
Free Lime	0.98	.....
Loss on Ignition	0.99	≤ 3
Insoluble Residue	0.6	≤ 1.5
Solid Solution	13.76	.....
Lime Saturation Factor	94.79	.....
C3S	56.39	.....
C2S	16.24	.....
C3A	5.79	.....
C4AF	9.17	.....
Physical Characteristics	Results	ASTM C150 Limitations
Blaine Surface Area [m ² /kg]	317	≥ 280
Initial Setting Time [min]	118	≥ 45
Final Setting Time [min]	350	≤ 375
Compressive Strength [MPa]		
3 days	14.21	≥ 12
3 days	22.13	≥ 19

River sand and crushed stone with a maximum aggregate size of 19 mm were utilized as NA, and both fine and coarse aggregates met ASTM C33-23 [14]. The particle size distribution of the natural fine and coarse aggregates is shown in Fig.1. The coarse RCA used in this study was created in a laboratory by crushing discarded concrete specimens from prior tests with a hammer to break them down into small particles (diameter 4.75–19 mm), as shown in Fig.2. Thereafter, the small particles were divided into different sizes using sieves, and these sizes were then placed to provide a gradient similar to the coarse NA used. Table 2 shows the physical properties of the aggregate that utilized in this research. All concrete specimens were prepared, mixed, and cured using potable tap water.

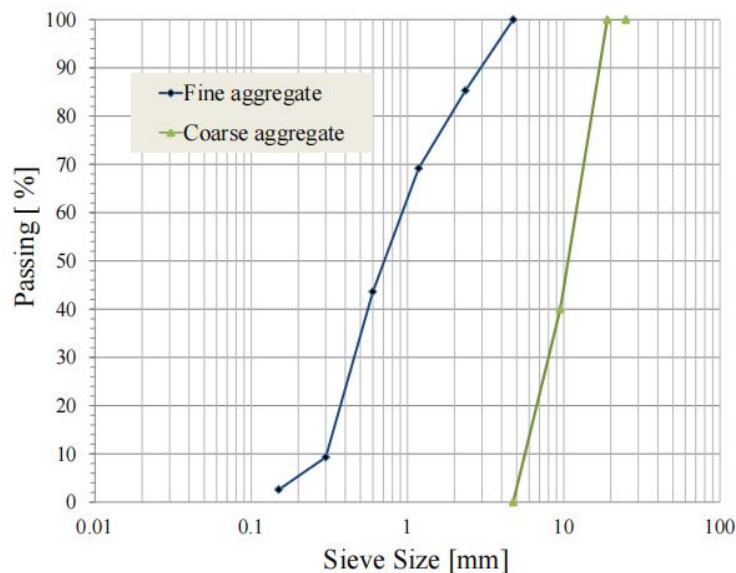


Fig. 1: Gradation of natural fine and coarse aggregate used.



Fig. 2: Recycled coarse aggregate preparation: a) Tested concrete specimens that were discarded, b) Natural and recycled coarse aggregates after sieving.

Table 2: Physical properties of the sand, crushed stone, and recycled coarse aggregate.

Property	Sand	Crushed stone	Recycled coarse aggregate
Fineness Modulus	2.9	6.6	6.6
Specific Gravity	2.67	2.60	2.47
Unit Weight [kg/m ³]	1232	1456	1199
Water Absorption [%]	1.0	1.01	3.95

2.2 Mix proportion and concrete mixing

An extremely dry control mixture was proportioned according to ACI 211.3R-02 [3]. The mixture details for the mixes made throughout the study are shown in Table 3. The reference mixture was manufactured using only NA, while the other concrete mixtures were manufactured by substituting coarse NA with various proportions of coarse RCA (by weight), including 25%, 50%, 75%, and 100%.

Table 3: Mix proportions of concrete mixtures.

Mix ID	Cement [kg/m ³]	Sand [kg/m ³]	Crushed stone [kg/m ³]	Recycled coarse aggregate [kg/m ³]	Water [kg/m ³]
ZSC0	350	535	1247	0	102.6
ZSC25	350	535	935.25	311.75	116.95
ZSC50	350	535	623.5	623.5	128.65
ZSC75	350	535	311.75	935.25	140.35
ZSC100	350	535	0	1247	152.05

Because coarse RCA absorbs more water than coarse NA, as shown in Table 2, recycled aggregate ZSC mixtures are frequently made using the recycled aggregate pre-saturation method or the mixing water adjustment procedure to match the same workability as the control mix [6]. So, the coarse RCA was used in this study in an air-drying condition, and the water content was adjusted based on the aggregates' actual moisture content and water absorption capabilities. For the manufacture of the concrete mixture, the aggregates and cement were blended for 3 minutes. Then, the water was added, and the ingredients were mixed for 10 minutes. Only a sufficient amount of water was used to create cohesive blends without a drop of slump (stiff concrete). The ASTM C143 [15] standard was followed for conducting the slump tests, as shown in Fig. 3. Finally, the obtained mixture was poured into a well-oiled mold and compacted by the vibration, and surface finishing was performed. The specimens were unmolded after 24 hours and maintained in a water curing tank at 23 ± 2 °C for 28 days until testing at 7 and 28 days. At 90 days, the specimens were also kept in water for 28 days, and then they were exposed to air at an ambient temperature of 25 ± 2 °C and a relative humidity of 55 ± 5 % until the testing day.



Fig. 3: Slump test of concrete mixtures.

2.3 Tested properties

At 7, 28, and 90 days, the compressive strength according to BS 1881-116:1983 [16] and ultrasonic pulse velocity according to ASTM C597 [17], were recorded on 150-mm cubic specimens. The flexural strength was recorded on 100 x 100 x 500 mm prism specimens according to ASTM C293 [18]. According to ASTM C642-21 [19], dry bulk density and water absorption in the study were assessed at 90 days on 100-mm cubic specimens. For each age, three specimens' mean values were recorded.

3 Results and discussion

3.1 Compressive strength

Fig. 4 displays the average compressive strength of ZSC mixes at 7, 28, and 90 days. The general trend for the 7, 28, and 90-day strengths is similar, and it is that the compressive strength declines as the coarse RCA content rises.

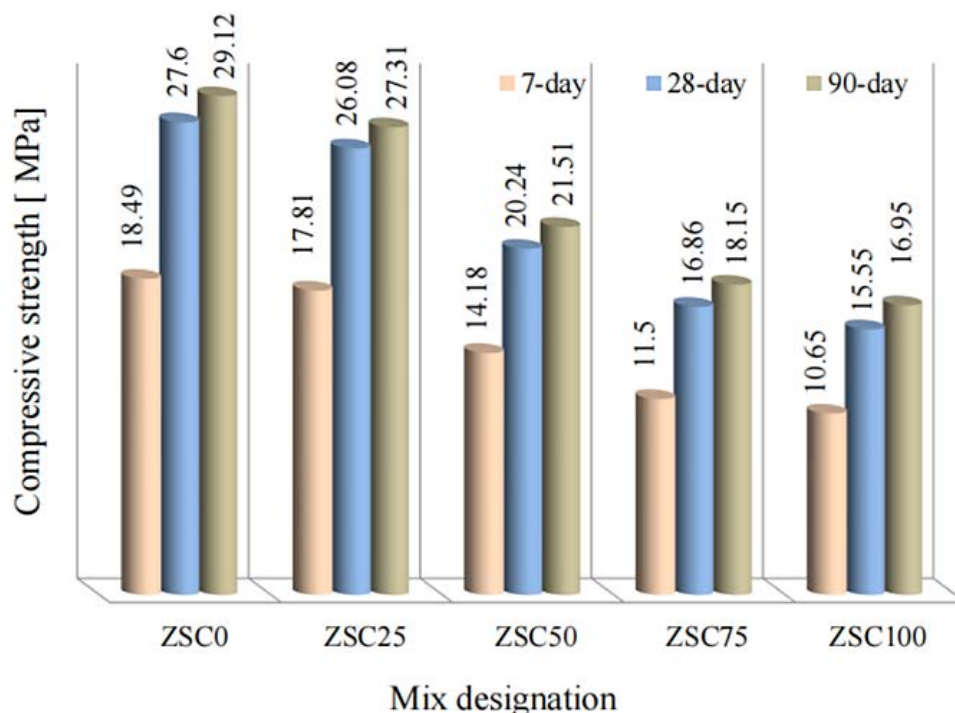


Fig. 4: Compressive strength of zero slump concrete mixtures at different ages.

As shown in Fig. 4, it can be seen that there is a significant difference in compressive strength with the change of replacement. At 7 days, there was a small drop of about 3.7% in the compressive strength of the reference mixture ZSC0 at 25% RCA substitution. When the replacement amounts were 50% and 75%, respectively, the decline grew to 23.3% and 37.8%. The greatest drop happened when the replacement quantity was 100%, reaching 42.4%. At 28 days, the decline behaviour was similar. In comparison to the reference specimens, the mixtures of ZSC25, ZSC50, ZSC75, and ZSC100 showed compressive strength losses of about 5.5%, 26.7%, 38.9%, and 43.6%, respectively. This trend was

also reproduced at 90 days, indicating that the mixtures of ZSC25, ZSC50, ZSC75, and ZSC100 showed compressive strength losses of about 6.2%, 26.1%, 37.6%, and 41.7%, respectively.

The results of the current study are supported by the findings of previous studies [11, 12, 20, 21]. The general mechanical characteristics of coarse RCA are lower than those of coarse natural aggregates since the majority of the coarse RCA is covered in old mortar, which typically has drawbacks including low strength, low density, numerous surface pores, excessive water absorption, and poor ability to bind with new mortar [8]. In addition, it becomes clear that coarse RCA is influenced by the original concrete's strength, the crushing machine, and the degree of crushing, and that the quality and composition of old mortar made from recycled aggregate from various sources vary greatly [20]. The surface of RCA is characterized by an extra-interfacial transition zone (ITZ) between the aggregate and the old mortar. ITZ is widely recognized as the weakest link in concrete. As a result of the existence of an additional ITZ in RAC, the compressive strength is reduced [22].

3.2 Flexural strength

The flexural strength of ZSC mixtures at 7, 28, and 90 days is shown in Fig. 5.

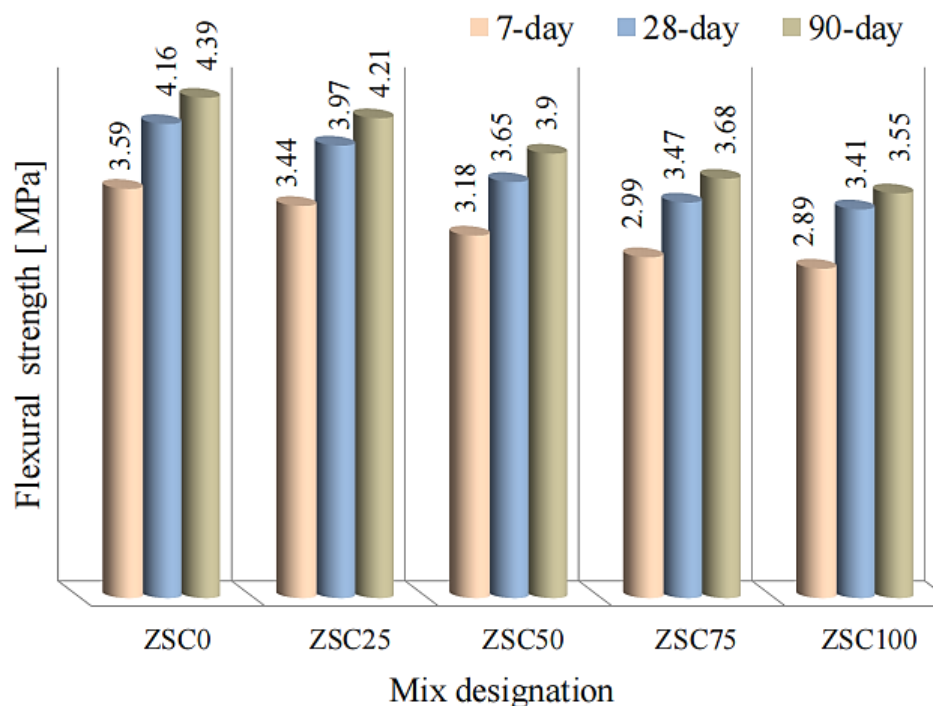


Fig. 5: Flexural strength of zero slump concrete mixtures at different ages.

As shown in Fig.5, the reference mixture ZSC0 at 25% coarse RCA substitution showed a slight decrease in flexural strength at 7 days of about 4.2%. The drop increased to 11.4% and 16.7% when the replacement rates were, respectively, 50% and 75%. The greatest drop happened when the replacement rate was 100%, reaching 19.5%. At 28 days, the decline behaviour was similar. In comparison to the reference mixture, the mixtures of ZSC25, ZSC50, ZSC75, and ZSC100 showed flexural strength losses of about 4.6%, 12.3%, 16.6%, and 18%, respectively. This pattern was replicated at 90 days, showing that the ZSC25, ZSC50, ZSC75, and ZSC100 mixtures had flexural strength reductions of about 4.1%, 11.2%, 16.2%, and 19.1%, consecutively.

The range of flexural strength decreases in the ZSC produced by the use of coarse RCA in the current investigation is lower than the range of compressive strength losses. In general, researchers [12, 21] highlighted a significant decrease in flexural strength when coarse RCA was utilized in a large proportion. One probably explanation for the main reason for generating flexural strength loss is the weak mechanical characteristics of coarse RCA. Since the impact force used to crush the aggregates could result in internal fissures, RCA are weaker than NA. The broken RCA may break even more when being mixed and blended [23]. The flexural strength of concrete decreased as a result of the lower elastic modulus of coarse RCA [23]. Additionally, the decrease could be attributed to the weak interfacial bond created between the new cement paste and the old cement paste surrounding the coarse RCA [8].

3.3 Ultrasonic pulse velocity

The average reading of the UPV of ZSC mixtures at 7, 28, and 90 days is shown in Fig. 6.

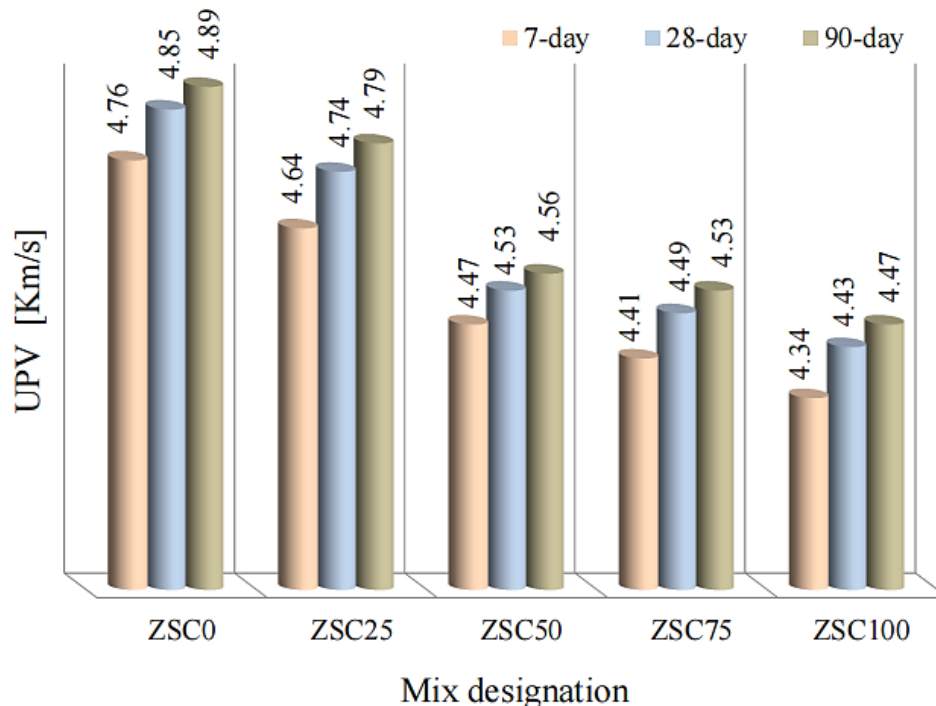


Fig. 6: Ultrasonic pulse velocity of zero slump concrete mixtures at different ages.

As shown in Fig. 6, all mixtures show similar patterns: a decrease in UPV as the coarse RCA content increases. The reference mixture ZSC0 at 25% coarse RCA replacement displayed a small drop in UPV of about 2.5% at 7 days. When the replacement rates were respectively 50% and 75%, the decline grew to 6.1% and 7.3%. The highest drop, 8.8%, was when coarse RCA completely replaced coarse natural aggregate. After 28 days, the declining behavior remained. In comparison to the reference mixture, the ZSC25, ZSC50, ZSC75, and ZSC100 mixtures showed UPV losses of about 2.3%, 6.6%, 7.4%, and 8.7%, respectively. This pattern was replicated at 90 days, showing that the UPV decreases in the ZSC25, ZSC50, ZSC75, and ZSC100 mixtures were 2%, 6.7%, 7.4%, and 8.6%, respectively.

Similar outcomes were found in previous investigations [12, 24]. According to the rating suggested by Malhotra [25], the specimens are classified as in "good" condition when their UPV values fall in the range of 4.34 km/s–4.89 km/s. All specimens are clearly in "good" condition at 7, 28, and 90 days, which means that the concrete does not have any major voids or cracks that might compromise structural integrity. The primary cause of the decline in UPV is attributable to two major factors. The first is that coarse RCA has a lower density (higher porosity) than coarse NA due to the presence of residual cement mortar with a lower density surrounding the recycled aggregate particles as well as to voids and cracks in the ITZ where the attached old aggregates and mortar are located [12, 24]. The second reason is that the surrounding mortar in RCA absorbs more water than NA and requires more water to achieve the same target slump as equivalent conventional concrete. As a result, the density of the cement paste declines because of the higher water-to-cement ratio [26]. So, the density of the concrete mix decreased. As the density drops, it takes more time for the ultrasonic pulses to travel throughout the length of a solid material [26].

3.4 Dry bulk density

The average values of the dry bulk density of ZSC mixtures after a curing period of 90 days are shown in Fig. 7. The findings show that as the RCA quantity increases, the bulk dry density significantly drops.

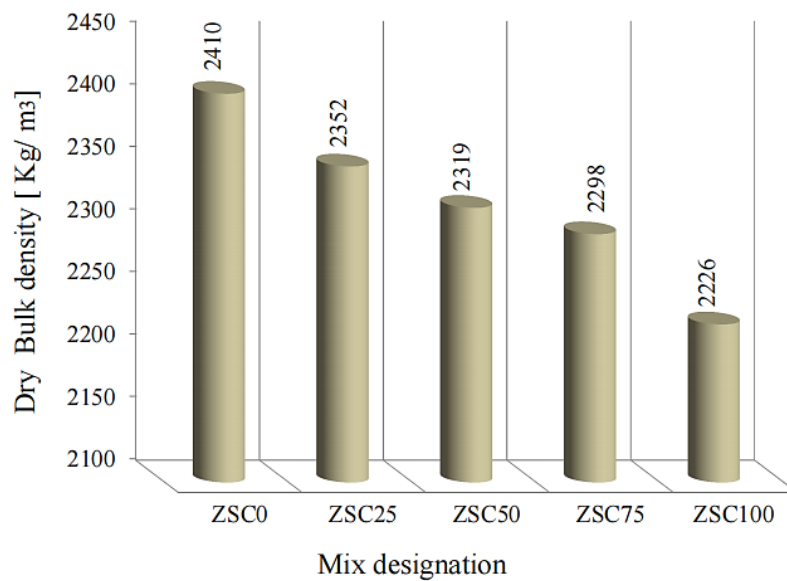


Fig. 7: Dry bulk density of zero slump concrete mixtures at 90 days.

At 25% coarse RCA replacement, the reference mixture ZSC0 displayed a decrease in dry bulk density of about 2.4%. The dry bulk density dropped to 3.8% and 4.7%, respectively, at replacement ratios of 50 and 75 percent. The largest decrease, 7.6%, was when coarse RCA completely replaced coarse natural aggregate.

Comparable outcomes from previous investigations have been reported [26, 27]. Hardened concrete density normally decreases as RCA content increases. This is mostly due to the reduced density of RCA, which results from the existence of residual cement mortar attached to the recycled aggregate particles that has a lower density [22]. Another explanation for the decline is that more water was needed in the RCA to achieve the desired slump, which reduced cement paste density. This is a result of RCA's greater water absorption [22]. However, a number of researchers [22, 26] show that the quality of the virgin aggregates rather than the quantity of bonded old cement mortar is more responsible for the low specific gravity of RCA. As a result, it is expected that the density of the RCA will be lower than that of the control mix.

3.5 Water absorption

The average values of the water absorption of ZSC mixtures at 90 days are shown in Fig. 8. The water absorption was shown to increase as the NA replacement increased.

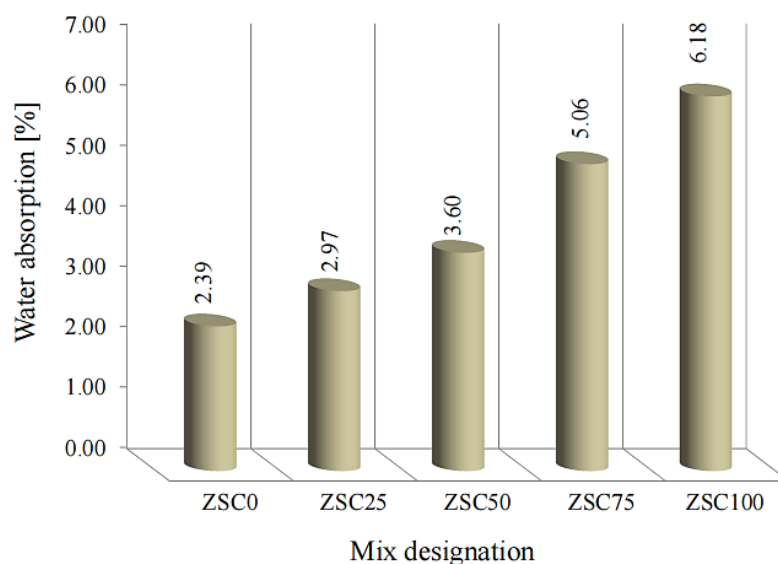


Fig. 8: Water absorption of zero slump concrete mixtures at 90 days.

The reference mixture ZSC0 showed a rise in water absorption of about 24.4% at 25% coarse RCA replacement. When the replacement ratios were 50 and 75 percent, the water absorption increased to 50.9% and 112.1%, respectively. When coarse RCA totally replaced coarse NA, the biggest increase, 158.8%, occurred.

In earlier investigations [11, 12] comparable results were reported. This excessive water absorption is mainly attributed to the presence of extremely porous mortar adhered to the surface of the parent concrete [23]. Furthermore, the microstructure of ITZ plays a role since it depends strongly on the type of aggregate, its porosity, and its water absorption properties. Because there is old adhesive mortar surrounding the recycled aggregate, the microstructure of the material is porous [24]. This porous ITZ has a significant impact on the absorption features of concrete, especially when individual ITZ regions link together across the three-dimensional microstructure [26]. Additionally, the produced microcracks during the manufacturing process of recycled aggregates are linked to the poor water absorption resistance of recycled aggregate concrete, making the concrete more susceptible to capillary absorption[23].

3 Conclusions

It is evident from the investigation's findings that the following conclusions can be drawn:

- 1) The inclusion of coarse RCA in ZSC degraded the quality of manufactured concrete. The increase or decrease in ZSC characteristics was caused by RCA's inherent features, such as a higher level of water absorption, a lower bulk density, and a lower specific gravity.
- 2) According to the compressive strength results, the compressive strength decreases as the coarse RCA% rises. At 90 days, there was a 43.6% drop in compressive strength for 100% coarse RCA, which was only 5.5%, 26.7%, and 38.9% at 25%, 50%, and 75% replacement, in comparison to the control mix ZSC0.
- 3) The results of flexural strength indicate that flexural strength declines with an increase in coarse RCA%. Flexural strength reduction amounts at 90 days of about 4.1%, 11.2%, 16.2%, and 19.1% of 25%, 50%, 75%, and 100% RCA mixtures, respectively, in comparison to the control mix.
- 4) UPV results show that UPV declines when coarse RCA% increases. At 90 days, the UPV of 25%, 50%, 75%, and 100% RCA mixtures was 2%, 6.7%, 7.4%, and 8.6% lower, respectively, than the control mix.
- 5) The results show a considerable drop in dry bulk density as the coarse RCA content increases. The dry bulk densities of the 25%, 50%, 75%, and 100% RCA mixes were 2.4%, 3.8%, 4.7%, and 7.6% lower, respectively, at 90 days, in comparison to the control mix.
- 6) The results reveal that water absorption increases with increasing percentages of coarse RCA quantity, with a minimum water absorption rise of 24.4% at 25% coarse RCA, increasing to 50.9%, 112.1%, and 158.8% at 50%, 75%, and 100% replacement, respectively, at 90 days.

Acknowledgement

The employees and technicians of the University of Mosul's College of Engineering's Construction Materials Testing Laboratory.

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