Suitability of Crushed Aggregate for Replacement of Natural Aggregate in Concrete Production

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Abstract

Today's massive construction sector growth in Iraq and other emerging nations has raised the demand for concrete and its raw materials, particularly aggregates. Massive amounts of fine and coarse aggregate were removed from riverbeds, which exhausted the material supply, altered the nature of the rivers, damaged their ecosystems, and produced millions of tons of boulders. Solving these issues becomes an environmental and sustainable construction demand. It was discovered that crushed fine and coarse aggregate formed from boulders can be used in concrete manufacturing as an alternative to river material. Therefore, this paper considers the fresh and mechanical properties of mixtures by replacing natural fine and/or coarse aggregate with crushed aggregate in mass ratios of 0%, 25%, 50%, and 100%. The experimental results indicate that with increasing the crushed aggregate replacement ratios, the concrete compressive strength, flexural strength, and splitting tensile strength have been improved; meanwhile, the workability is significantly reduced in various ratios. This study revealed that crushed fine and coarse aggregate formed from boulders can be used in concrete manufacturing as a suitable alternative to river material, which will reduce environmental damage and ensure that resources are used as efficiently as possible without adversely affecting the strength of concrete.

Keywords

Environmental issues; aggregate extraction; sustainable concrete production; fresh properties; mechanical properties;

1. Introduction

In order to satisfy the demands of globalization and sustainable development, particularly after the high rate of population growth, Iraq, as a developing country, has recently taken a significant push to develop infrastructures like residential buildings, high-rise buildings, express highways, bridges, industrial constructions, etc. Moreover, in most cities, there are many completely new residential areas under construction, including the construction of all services and facilities[1]. Concrete performs the proper function in building construction and is used in significant quantities. Throughout history, people have used natural resources to make construction materials, and nearly all of the components of concrete are made from natural resources. The environment is threatened by growing pollution from the construction sector as a result of this ongoing exploitation.[2-4]. As a result, the provision of construction materials and ensuring environmentally friendly, sustainable development are two issues that the construction sector must deal with.

The most popular fine and coarse aggregate for use in construction is natural river aggregate as it is one of the main ingredients needed to make ordinary concrete[5]. Reports claimed that sand and gravel are the second-largest materials harvested and sold after water. The fine and coarse aggregates typically make up (65-75%) of the volume of the concrete and have a big impact on the ratios of the mixture, the economy, and the characteristics of the freshly mixed and hardened concrete. [6]. The aggregate is becoming very expensive and in short supply. With such a harmful environment, there is a high demand for alternative materials for natural river fine and coarse aggregate[7, 8]. According to a recent UN Environment assessment, aggregate exploitation in streams has increased pollution, floods, the depletion of water supplies, and the frequency of droughts, despite the fact that the world needs 40 to 50 billion tons of aggregates annually[9].

The extended geological progress of weathering and destruction by different geological factors, such as water, wind, flooding, etc., results in the formation of sand and gravel[10]. The amount of sediment that rivers dump along coastal areas and deltas has decreased as a result of dam construction and extreme and non-scientific aggregate extraction, yet beach erosion has grown[11]. Floods have become more regular and severe as a result of unstable riverbanks. Aquifers' groundwater levels have decreased. Drought frequency and severity have both risen. Moreover, increasing the risk to the environment by decreasing the water table, sinking bridge piers, causing river sides to slide, etc.

The most important issue is that, the extraction process has numerous negative effects on the environment. Almost all of the natural vegetation and top soil should be eliminated when digging the pits in order to reach the aggregate underneath. Due to the degradation of aquatic and plant ecosystems, this causes the extinction of current animal populations as well as a major loss of biodiversity. Furthermore, pollution, tainted water, dust, and noise all have an impact on nearby eco-systems. Pits can impair the quantity and quality of drinking water for locals and wildlife near or downstream from a quarry site. They can interfere with the circulation of surface water and groundwater. Additionally, the extraction process resulted in collecting and depositing millions of tons of boulders that covers large areas around the rivers and become another environmental issue, as shown in Fig. 1.

Fig. 1 Impacts of extraction process on environment

To solve the above-mentioned issues and minimizing the impact of aggregate extraction on the ecosystem and encourage sustainable growth of construction sector, many engineers and environment conservation organizations have called for establishing rules and regulations to prohibit or restrict the extraction process from the rivers[12]. Recently, they have suggested crushing the compiled oversize gravel and boulders and producing manufactured coarse and fine aggregate[13]. The case that will contribute to return the wildlife and vegetation life to the river bed and sides, also the flood and erosion gradually will start to backfill large pits and quarries around the river stream.

On the other hand, the quality assurance of aggregate is very crucial to obtain strong, durable and reasonably priced concrete. High-quality infrastructures are produced by using high-quality building materials. Such products should have their quality thoroughly evaluated in a recognized lab using accepted test procedures. The rheological and mechanical characteristics of concrete are significantly influenced by the aggregates. Aggregate characteristics such as specific gravity, particle gradation, form, and surface roughness significantly affect the characteristics of freshly mixed concrete[14]. Conversely, it is typically discovered that the mechanical characteristics of concrete are influenced by the aggregate mineralogy, surface texture, elastic modulus, and aggregate content ratio[15-17]. In order to guarantee the quality and endurance of the final building constructed using these materials, it is essential to conduct a full evaluation of their qualities[18, 19].

Zhao et al. [7] investigated the influence of crushed sand and included stone dust ratio on the workability of fresh concrete, include using three grades of concrete strength. They concluded that the existing of dust in crushed sand absorb the mix water and reduce the workability and the optimum stone powder content was 9%. Wakchaure et al.[20] considered the outcome of replacing natural sand by artificial sand on mechanical properties of concrete. They reported that the concrete compressive strength and flexural strength increased when artificial sand was used. Rajput et al.[21] studied the workability and compressive strength of concrete with replaced natural fine aggregate by quarry dust. They reported that with increasing the replacement ratio the workability increased while the compressive strength improved up to 40% replacement ratio then it decreased for 100% replacement ratio. Hong et al. [22] inspected the influence of coarse aggregate type (granite, basalt and limestone) and surface irregularity on splitting tensile strength and compressive strength of concrete. They reported that higher mechanical properties are produced when the roughness of the aggregate surfaces is too high. Pilegis et al. [12] presented an investigation on concrete properties with replacing 100% sea sand by crushed sand. The findings demonstrate that because the manufactured sand particles are more angular than natural sand particles, manufactured sand concrete generally needs a greater water/cement ratio to be as workable as natural sand concrete. The hardened characteristics of crushed sand concrete are greater than those of natural sand concrete with the same water and cement content.

Based on the above literature review, investigations on concrete properties by replacing both fine and coarse aggregate with crushed ones is limited. Therefore, this study was motivated to investigate and compare the fresh and mechanical characteristics of concrete made from natural and crushed fine and coarse aggregate. In this study, ten mixtures have been prepared and tested, in each mixture, 0%, 25%, 50%, and 100% of the natural river fine and/or coarse aggregate were replaced by crushed fine and/or coarse aggregate.

2. Research Significance

Nowadays, due to the huge expansion of construction sector in Iraq and other developing countries, the demand of concrete and then its raw materials, particularly aggregates, are increased. Extracting huge amount of fine and coarse aggregate from the river beds depleted the available material, destroyed the nature of the rivers, and harm the environment of the rivers, as well as, resulted in millions of tons of oversized aggregate and boulders. It was found that, an alternate to river aggregate is to use crushed fine and coarse aggregate made from boulders in concrete manufacturing. Therefore, investigating the properties of concrete constructed from crushed fine and coarse aggregate is an economic and environmental demand.

3. Testing Program

The purpose of the current study is to consider the mechanical properties of concrete specimens with various replacement ratio of natural fine and coarse aggregate by crushed fine and coarse aggregate. Therefore, a mix proportion was selected to get a target concrete compressive strength of 25MPa. For the selected mix, ten mixtures were used with crushed fine and/or coarse aggregate replacement ratios of 0%, 25%, 50%, and 100% instead of natural fine and/or coarse aggregate. For each mixture a set of specimens were casted and tested which were; nine cubes of 100×100×100mm, three prisms of 75×75×375mm, and three cylinders of 100x200mm.

3.1 Materials

3.1.1 Cement

Ordinary Portland cement grade R42.5, which complies with standard specification of ASTM C150[23] and C114[24], was used to prepare the mixtures. It was brand-new, free of any extraneous materials, and put through testing to guarantee laboratory quality control. Table 1 lists the cement's characteristics.

Table 1 Chemical analysis of tested cement

Content	CaO	SiO2	Al2O3	MgO	SO3	Fe2O3	K2O	Loss on Ignition	Insoluble Residue
Results	57.2 %	23.6 %	5.2%	3.6 %	1.8 %	0.9%	0.41 %	1.1%	0.22%

3.1.2 Natural and crushed aggregate

The characteristics of fresh concrete are significantly influenced by the aggregate gradation. An aggregate's sieve analysis provides a percentage of the material that passes through an opening of a specific size. The properties of the whole amount of the aggregate to be utilized will be revealed by a representative sample that has been tested. The source of natural fine and coarse aggregate is from Sirwan river in east of Kurdistan Region, north-east of Iraq. A well-graded natural river fine and coarse aggregate were used which was extracted, screened, and washed from the river. The crushed fine and coarse aggregate were obtained from crushing of natural boulders. The photo of used fine and coarse natural/crushed aggregate is shown in Fig. 2. The results of the physical tests performed on the used crushed and natural aggregate are given in Table 2. The specific gravity and bulk density are almost the same for both crushed and natural aggregates. The fineness modulus of crushed fine aggregate is 2.25 and for the natural fine aggregate is 2.60, this indicate that the crushed fine aggregate is much finer than the natural one. The crushed value and impact value for crushed coarse aggregate is more than the natural coarse aggregate, which indicate that the natural aggregate is stronger than the crushed one. The maximum aggregate size of both natural and crushed coarse aggregate was 12.5mm. The grading curve and ASTM C136 limits[25] for natural aggregate and crushed aggregate are shown in Fig. 3 and Fig. 4 respectively.

Fig. 2 Photo of used fine and coarse natural/crushed aggregate

Table 2 Properties of aggregate

Material	Specific gravity gm/cm^3	Water Absorption	Fineness Modulus	Bulk Density, gm/cm^3	Crushed Value %	Impact Value %
Natural Fine Aggregate	2.70	1.45%	2.60	2.26		
Natural Coarse Aggregate	2.68	1.35%		2.59	32.5	12.9
Crushed Fine Aggregate	2.69	1.52%	2.25	2.42		
Crushed Coarse Aggregate	2.68	4.0%		2.55	37.1	16.4

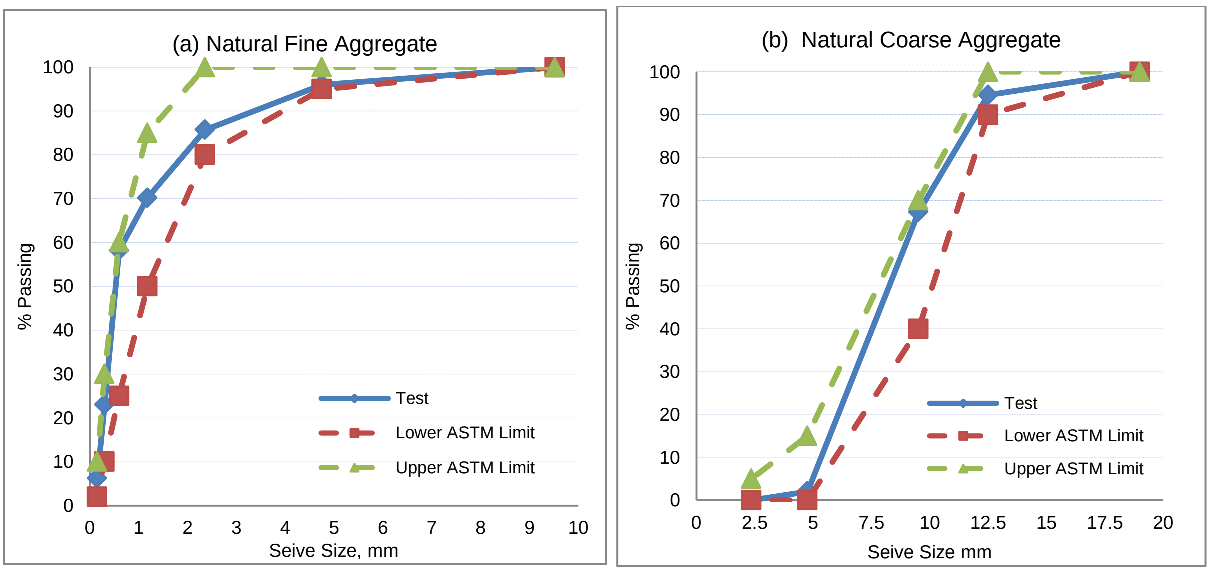

Fig. 3 Grading curves and ASTM limits for (a) natural fine aggregate, (b) natural coarse aggregate

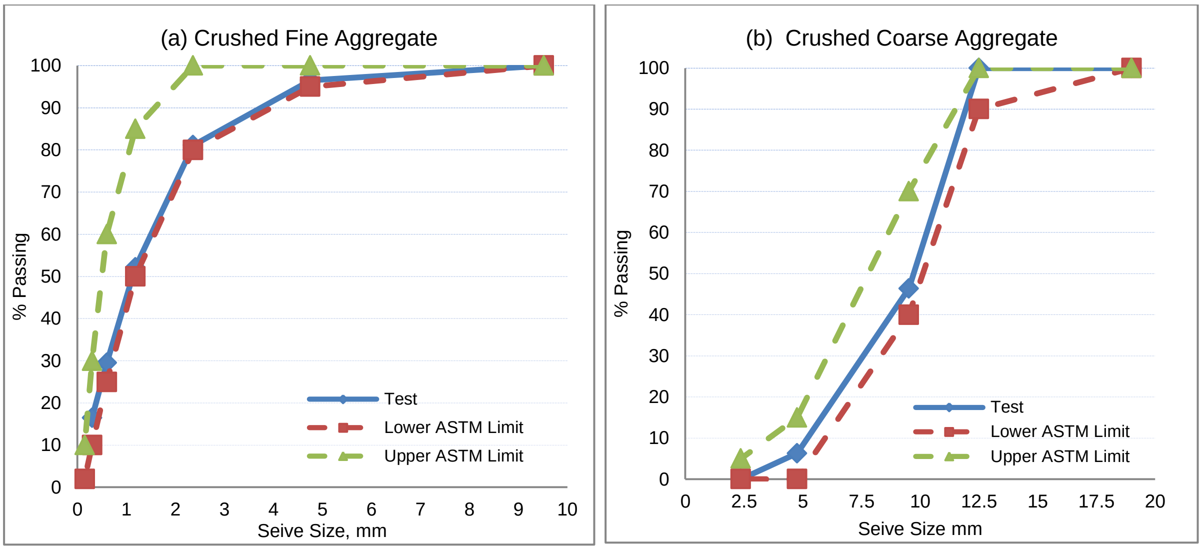

Fig. 4 Grading curves and ASTM limits for (a) crushed fine aggregate, (b) crushed coarse aggregate

3.2 Specimens preparation

Table 3 displays the specifics of the designated mix magnitudes for each mixture. Using a traditional mixer with a capacity of 0.022 m^3, raw materials were mixed to produce homogeneous concrete with appropriate characteristics. The coarse aggregate and fine aggregate were first poured, then about 20% of the water was added to moisten the aggregate, and mixing proceeded for a minute before the addition of cement and then the rest of water was added. The mixing process was continued until regular concrete mixture was created. Beginning with three layers of concrete mixture into the standard molds, the casting process was vibrated using a typical vibration table in accordance with ASTM C192[26]. The specimens underwent a 28-day curing process within the lab while submerged in a curing tank, as shown in Fig.5.

Fig. 5 Concrete specimens after curing

Table 3 Composition of the concrete mix (kg/m^3)

Mixtures	Cement, Kg	Natural Sand, Kg	Natural Gravel, Kg	Crushed Sand, Kg	Crushed Gravel, Kg	W/C
M1	335	834	1002	0.0	0.0	0.6
M2	335	625.5	1002	208.5	0.0	0.6
M3	335	417	1002	417	0.0	0.6
M4	335	0.0	1002	834	0.0	0.6
M5	335	834	751.5	0.0	274.5	0.6
M6	335	834	501	0.0	501	0.6
M7	335	834	0.0	0.0	1002	0.6
M8	335	625.5	751.5	250.5	274.5	0.6
M9	335	417	501	417	501	0.6
M10	335	0.0	0.0	834	1002	0.6

4. Results and Discussion

The aim of this investigation is to consider the full and partial replacement of fine and/or coarse natural aggregate by fine and/or coarse crushed aggregate to compare the mechanical properties of the concrete mixtures. A total of ten mixtures were equipped and specimens were casted, cured and tested with replacement ratios of 0%, 25%, 50% and 100% for replacement of fine aggregate, coarse aggregate or both of them. Photos of concrete specimens during the test are shown in Fig. 6 and the results of the tested specimens are shown in Table 4.

Table 4 Test Results of the Concrete Specimen

Mixtures	Density, kg/m3	Slump, mm	Compressive strength, fcu, MPa		Split tensile strength, fct (MPa)	Flexural strength, fr (MPa)
			7 days	28 days		
M1	2362.8	170	12.1	23.3	4.85	4.85
M2	2367.0	140	13.7	24.3	4.71	4.71
M3	2352.0	95	13.0	25.1	4.21	4.21
M4	2371.0	15	14.9	25.7	3.89	3.89
M5	2365.3	125	14.7	27.3	3.67	3.67
M6	2378.0	115	14.9	28.2	4.33	4.33
M7	2365.5	35	16.3	28.0	4.17	4.17
M8	2387.3	80	15.4	29.5	3.35	3.35
M9	2385.2	30	15.1	29.4	3.43	3.43
M10	2392.3	5	16.1	27.1	3.86	3.86

Fig. 6 Concrete specimens testing

4.1 Slump

In order to prevent problems with handling costs, low strength, and poor durability, an appropriate concrete mixture should be easily mixed, handled, laid in its final position, and properly compacted. The concrete workability is implicitly assessed by its consistency. Concrete's consistency is largely affected by the physical characteristics of the fine and coarse aggregate. For all mixtures the fresh properties of concrete were measured for workability by a standard slump cone according to ASTM C143[27]. The photos of slump testes are shown in Fig. 7 and the results are presented in Fig. 8. It can be observed that the slump flow reduced with increasing the replacement ratio of natural fine and/or coarse aggregate crushed ones. For specimens, M2, M3, and M4, with crushed fine aggregate replacement ratios of 25, 50, and 100%, the reduction in slump values compared to reference sample, M1, are 17%, 44%, and 91% respectively. While the slump reduction ratios are smaller in specimens, M5, M6, and M7, with respect to reference sample, which are 26%, 32%, and 79% respectively. This implies that the crushed fine aggregate reduced the workability more than the coarse aggregate, which may be attributed to the smaller fineness modulus and higher particle angularity of crushed fine aggregate compared to natural fine aggregate. Moreover, the fineness modulus of both natural and crushed coarse aggregate are similar, but the particle angularity and surface roughness are higher in crushed aggregate compared to natural aggregate. Furthermore, for the specimens of M8, M9, and M10, where both natural fine and coarse aggregate were replaced by crushed fine and coarse aggregate, the slump ratios reduced significantly to about 53%, 83%, and 97% respectively. This significant reduction in workability caused by the combined effect of both fine and coarse crushed aggregate which are; higher water absorption, smaller fineness modulus, higher ratio of particle angularity shape, and more rough surface texture of particles. These outcomes are compatible to the studies of Zhao et al. [7] and Pilegis et al. [12] as they claimed that the existing of dust in crushed sand absorb the mix water and reduce the workability. Therefore, more water content and may be more cement paste are required to increase the workability and overcome the work needed to reduce the internal friction between aggregate particles. Another solution to obtain workable mixture when crushed fine and/or coarse are used is to use admixtures like superplasticizer in suitable ratios which may be investigated in future works.

Fig. 7 Slump test

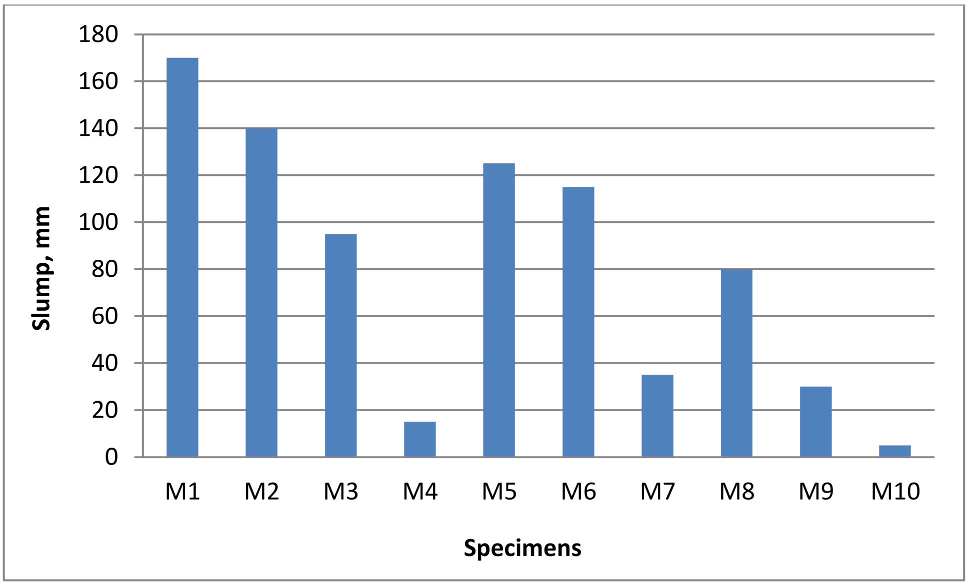

Fig. 8 Slump test results

4.2 Concrete Compressive strength

The compressive strength of the concrete is the most important parameter used in the construction of reinforced concrete structures. Based on the requirements of EN 12390-3:2019[28], the concrete compressive strength, fcu, was determined by testing 100x100x100mm cubes. When the seventh or the twenty-eighth day of curing had been successfully completed, the samples were removed from the curing tank and allowed to dry for 24 hours before testing. En 12390 specifies that the rate of loading for compressive strength must be kept within 0.3-0.34 MPa/s. The outcomes of the concrete compressive strength are displayed in Table 4 and more prominently exhibited in Fig. 9.

Generally, the concrete compressive strength at 7- and 28-day ages improved with increasing the replacement ratio of natural fine and/or coarse aggregate by crushed ones. For specimens, M2, M3, and M4, with crushed fine aggregate replacement ratios of 25%, 50%, and 100%, the ratio of concrete compressive strength slightly increased compared to reference sample, M1, by about 4%, 7%, and 10% respectively. While the concrete compressive strength increased in larger ratios in specimens, M5, M6, and M7, with respect to reference sample, which are about 17%, 21%, and 20% respectively. This specifies that the crushed coarse aggregate improved the concrete compressive strength more than the crushed fine aggregate, which may be attributed to the larger bond between the cement paste and the aggregate particles as a result of the rough surface texture and angular shape of coarse aggregate particles compared to natural aggregate. Moreover, the water absorption ratio of crushed coarse aggregate is more than the natural aggregate which contribute to decrease the mix water and then increase the concrete compressive strength. Furthermore, for the specimens of M8, M9, and M10, where both natural fine and coarse aggregate were replaced by crushed fine and coarse aggregate, the concrete compressive strength ratios increased to about 26%, 26%, and 16% respectively. The relatively low increase ratio of specimen M10 compares to M8 and M9 may attributed to the stiff mixture and large reduction in workability, as 100% of crushed aggregates were used which may have caused weak points of small segregation in specimens. These results confirm that using crushed fine and/or coarse aggregate give larger concrete compressive strength' however more water may be needed to improve the mixture's workability in proportion to the replacement ratio.

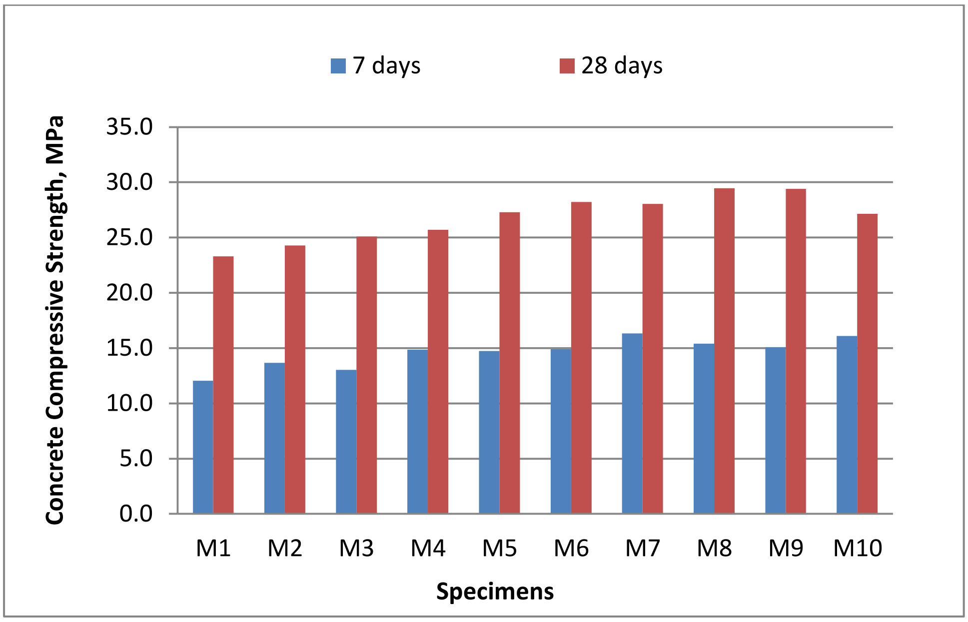

Fig. 9 Concrete compressive strength of 7- and 28-days test results

4.3 Splitting tensile strength

For the purpose of measuring the splitting tensile strength, three 100×200 mm cylinders were prepared for testing. The results of the average tensile strength are displayed in Table 4 and Fig. 10. The indirect tensile strength of the specimens was tested and calculated using ASTM C 496[29] under a rate of loading between (1.2-2.4) MPa/min. The discrepancy of splitting tensile strength results for most of the specimens are comparable to that of compressive strength results. As can be observed with the addition of crushed fine and/or coarse aggregate, the splitting tensile strength improved related to reference specimen. The improved ratios were about 2%, 4%, 9%, 4%, 12%, 25%, 22%, 26%, and 37% for specimens of M2, M3, M4, M5, M6, M7, M8, M9, and M10 respectively. These results may be caused by the high bond strength among the aggregate particles and cement paste as a result of the differences in physical characteristics of crushed aggregate compared to natural ones. Other factors that may cause these results are; high content of fines, rough surface texture, angularity shape, and high water absorption capacity of the crushed fine and coarse aggregate that will likely result in concrete with higher strength.

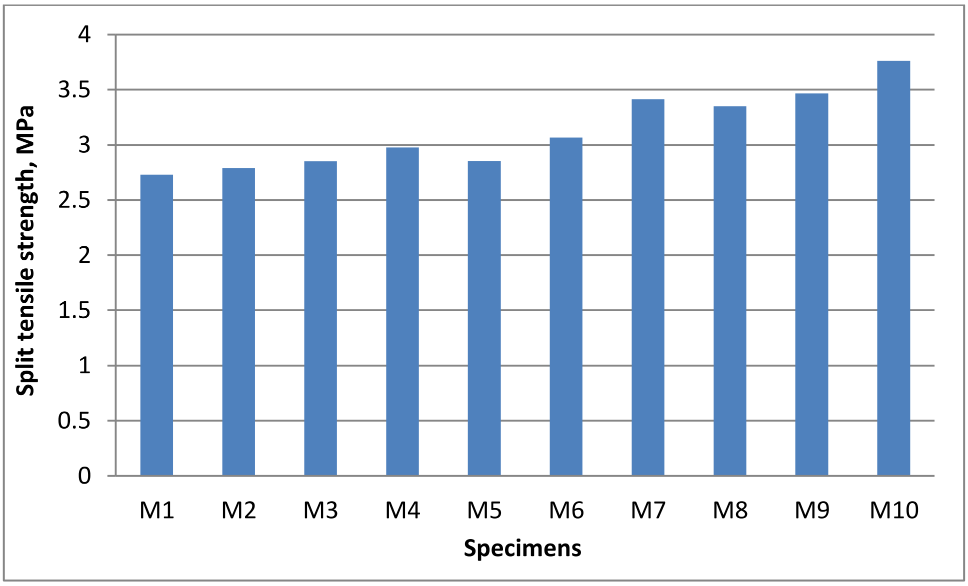

Fig. 10 Split tensile strength of test results

4.4 Flexural strength

Another indirect tensile strength test of concrete is the flexural strength of prisms which follow the behavior of split tensile strength according to ASTM C78[30]. Table 4 and Fig. 11 show the experimental test results of flexural strength for all tested specimens. Generally, it can be noted that similar to splitting tensile strength the flexural strength of concrete improved with increasing the crushed fine and/or coarse aggregate replacement ratios. The flexural strength increased in ratios of 4%, 7%, 9%, 16%, 20%, 19%, 24%, 22%, and 16% for specimens of M2, M3, M4, M5, M6, M7, M8, M9, and M10 respectively. These results may be attributed to the same factors that caused the strength growth of splitting tensile strength. Similar results were demonstrated by many other studies[12, 20, 21] as they experimentally tested concrete with replaced natural fine aggregate by crushed aggregate.

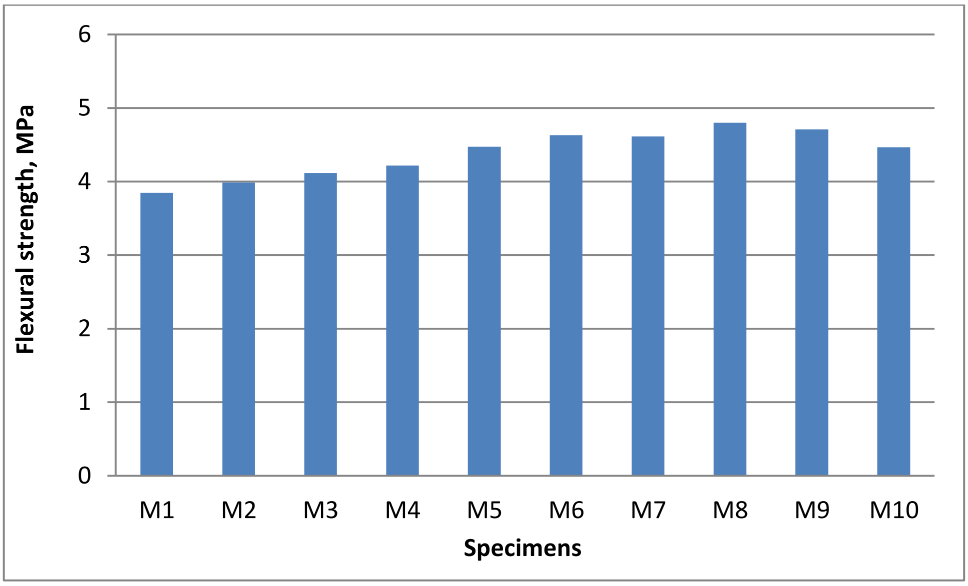

Fig. 11 Flexural strength of test results

Conclusions

The current study investigates the fresh and mechanical properties of concrete specimens, in which the natural fine and/or coarse aggregates were replaced by crushed aggregates in ratios of 25%, 50%, and 100%. The properties of a total of 10 mixtures have been measured and investigated which led to obtain the following conclusions:

- The workability of mixtures significantly reduced when the natural fine and/or coarse aggregate were replaced by crushed ones, the reduction ratio increased with the increase of replacement ratio. This behavior caused by the physical properties of both fine and coarse crushed aggregate which are; higher water absorption, smaller fineness modulus, higher ratio of particle angularity shape, and more rough surface texture of particles. Therefore, more water content and may be more cement paste are required to increase the workability of the mixture.

- As a solution to obtain workable mixture when crushed fine and/or coarse aggregate are used is to use admixtures like superplasticizer in suitable ratio which may be investigated in future works.

- The concrete compressive strength slightly increased with the increase of replacement ratio of natural fine and/or coarse aggregate by crushed ones with the same water-cement ratio. This may be attributed to the larger bond between particles and cement paste due to the rough surface texture and angular shape of crushed aggregates. Moreover, the water absorption ratio of crushed aggregate is more than the natural aggregate which contribute to decrease the mix water and then increase the concrete compressive strength.

- Both the splitting tensile strength and flexural strength increased as the replacement ratio of natural fine and/or coarse aggregate by crushed aggregate increased, as a result of many factors like; high content of fines, rough surface texture, angularity shape, and higher water absorption capacity of the crushed aggregate that will likely result in concrete with higher tensile strength.
- This study revealed that crushed fine and coarse aggregate formed from boulders can be used in concrete manufacturing as a suitable alternative to river material. Therefore, producing concrete with crushed aggregate significantly contribute to hassle the environmental problems of rivers and develop sustainable construction
- The stakeholders, country administration's construction departments should encourage the parties involved in construction on the use of crushed aggregate as a partial or full replacement for natural aggregate in order to reduce environmental damage and ensure that resources are used

as efficiently as possible without adversely affecting the strength of concrete.

- It is advised that future researchers perform additional research on crushed fine and/or coarse aggregate as a partial or full replacement of natural aggregate for concrete manufacture; like studying; modulus of elasticity, ultrasonic pulse velocity, rebound hammer test, high strength concrete, and self-compacted concrete.

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