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Utilization of Locally Available Waste Material for Sustainable Construction

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Abstract

The increasing demand for natural aggregate in concrete production, along with the increasing production of waste due to industries and constructions, has created concerns regarding resource depletion and environmental degradation. Utilization of wastes in concrete mixes is a very effective method to save the natural resources as well as construct environmentally friendly buildings. In this paper, the performance of M40 grade concrete is examined through the use of silica fume, quarry dust, and ceramic wastes as partial replacements of conventional materials. Quarry dust is used in place of fine aggregate, and ceramic waste is used in place of coarse aggregate. Silica fume content varies from 6% to 9%, replacement level for quarry dust ranges from 10% to 40%, and replacement level for ceramic waste changes from 10% to 40%. Properties of raw materials were determined by specific gravity and sieve analysis tests before mix design. Characteristics of fresh concrete were measured using slump tests, and those of hardened concrete were measured by compressive strength, split tensile strength, and flexural strength tests. The effect of quarry dust, ceramic waste, and silica fume additions was reflected on the behavior of the concrete mixtures in terms of both workability and compressive strength. In the range of the tested combinations, the best compressive strength, which was equal to 53.33 MPa, was attained for the combination of 6% silica fume, 10% quarry dust, and 10% ceramic waste. This level of compressive strength was higher than the required compressive strength for M40 concrete. It is clear that the increase in the strength properties could be contributed by better packing and densification of the concrete due to the effects of silica fume and finely graded quarry dust. Nevertheless, higher proportions

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of these additives had negative impacts on the strength of concrete because of the increase in void age and poor interfacial bond between aggregates and paste.

Keywords: Quarry Dust, Ceramic Waste, Sustainable Concrete, M40 Mix Design, Compressive Strength, Waste Utilization.

1. Introduction

Concrete continues to be the most widely used construction material because of its versatility, strength, and economic viability. The increasing need for development has greatly impacted the availability of resources like river sand, crushed stones, and gravel, since their excessive exploitation leads to resource depletion, ecological deterioration, loss of biodiversity, and environmental pollution. Therefore, the construction sector is focusing on developing sustainable alternatives that will minimize the dependence on traditional materials while still meeting the structural specifications required by concrete mixes.

In addition, industrial and construction wastes continue to be produced every year as by-products of processes like manufacture and processing. Among such industrial and construction wastes are quarry dust and ceramic wastes, which have become environmental problems due to their disposal needs and land occupation. Quarry dust comes from the process of quarrying in aggregate production plants. Due to the properties of angularity and mineralogy, quarry dust may serve as an alternative for fine aggregate because of the fineness of its particle size. In contrast, ceramic wastes that come from rejected tiles, sanitary wares, and damaged ceramic products are hard and durable.

In previous studies, it was found that the addition of ceramic wastes and quarry dust is helpful in obtaining sustainable concrete with minimized impact on the environment due to waste disposal and depletion of natural aggregates [1]–[7]. It is known that the addition of quarry dust assists in packing of particles and helps decrease voids inside the concrete mass, thus resulting in improved mechanical properties at optimal levels of replacement [2], [7]. The ceramic waste aggregates have demonstrated good strength and durability properties if added to the concrete mixture after proper processing [1], [4], [6].

Besides the aggregate replacement technique, supplementary cementitious materials are gaining importance nowadays to improve the microstructure of concrete. Silica fume is known for its excellent reactive pozzolana quality, possessing particles of ultra-fine nature. In addition to this, silica fume helps refine pores, improve the interface transition zone quality and formation of secondary C-S-H gel. The use of silica fume can make up for any reduction in strength caused by the use of waste aggregate replacement. Though several studies have been performed on ceramic waste and quarry dust individually, very few studies have tried to investigate both the materials together in M40 grade concrete using silica fume. The variations in the material qualities and proportions along with their local availability justify the need for experimentation to determine suitable proportions that can ensure desirable mechanical and environmental properties. Accordingly, the current study aims to investigate the suitability of the use of locally available quarry dust and ceramic waste as waste aggregates replacement materials in M40 grade concrete containing silica fume. Physical characteristics of the materials were evaluated, and the effect of proportion changes on the workability, compressive strength, split tensile strength, and flexural strength was investigated.

2. Literature Review

The rising requirement for sustainable building materials has led to the study of the use of industrial and construction wastes as substitutes in concrete. Among many types of waste-derived materials, ceramic waste and quarry dust have received much attention owing to their abundant sources, desirable properties, and ability to decrease reliance on natural aggregates. Several studies have found that the use of ceramic waste in concrete will not only help to save natural resources but also provide concrete with good strength and durability as long as proper substitution rates are adopted [1]. Another advantage of recycling ceramic waste in construction materials is the reduction of landfills [6].

The production of quarry dust as an inevitable byproduct through rock crushing operations is becoming more popular due to its effectiveness as a substitute for natural fine aggregate. Quarry dust possesses favorable physical properties such as good gradation and irregular particle shape that help to improve particle packing and matrix density in concrete mixes. Evaluations conducted on cementitious composites containing quarry dust revealed that partial substitution of quarry dust in place of natural sand could increase the mechanical properties and minimize the adverse effects associated with the mining of river sand [2]. Various tests also showed that quarry rock dust as fine aggregate substitution material could increase mechanical performance within optimum replacement ratios [7].

The simultaneous use of ceramic waste and quarry dust has been studied for the purpose of increasing sustainability and enhancing mechanical properties of concrete. It has been found that replacing the ordinary aggregates with ceramic waste and quarry dust can give rise to concrete with acceptable compressive strength and performance capabilities. The abrasive texture and angular shape of ceramic fragments enhance the interaction between aggregates, whereas the addition of quarry dust helps in minimizing internal voids in concrete [3]. This phenomenon has also been observed in concrete mixes that contain ceramic waste aggregates with similar strength properties to those of regular concrete [4].

Innovations in the field of sustainable concrete mixes have made it possible to go beyond the use of ceramic waste and quarry dust. In order to increase mechanical performance and decrease environmental costs, it is possible to add marble dust, industrial byproducts and reinforcing fibers to concrete. Modern approaches to optimization and predictive models make it easier to design environmentally friendly concrete mixes with desirable mechanical properties [5]. All these innovations contribute to creating green concrete with the minimum consumption of natural resources and carbon footprint [8].

Fundamental understanding of concrete behavior still needs to be considered in order to study alternative aggregate materials. Physical, mechanical, and durability properties of concrete are dependent on such parameters as aggregate grading, shape of particles, water-cement ratio, nature of interface transition zone, and curing conditions [9]. The use of waste materials changes these parameters and affects performance of fresh and hardened concrete. Principles of modern concrete technology prove that certain levels of optimum replacement are required [10].

Despite the fact that ceramic waste and quarry dust have been already found applicable both separately and in combinations, differences in properties of material, levels of replacement, and local availability of aggregates make it necessary to conduct additional research aimed at assessing potential of locally obtained quarry dust and ceramic waste for aggregate replacement in concrete of M40 grade combined with silica fume. This will allow developing sustainable construction technologies based on the principles of waste management, resource conservation, and minimization of negative impact on environment.

3. Materials and Methods

3.1 Constituent Materials

Ordinary Portland Cement (OPC) of grade 53, conforming to specifications as per Indian Standards, was chosen as the main cement binder due to its high efficiency in preparing concrete with strength properties, with a density of 3.20. Natural river sand with Zone II grading and fineness modulus of 2.51 with a density of 2.60 was selected as a reference fine aggregate. Crushed granite aggregate of nominal maximum size 20 mm and density 2.90 was used as a typical coarse aggregate. Locally obtained quarry dust, which includes angular fine aggregates less than 4.75 mm, that could be used as a partial substitution to the fine aggregates in view of their improved particle packing characteristics, was employed. In addition, processed waste ceramic material of tiles and sanitary wares were substituted partially to the coarse aggregates. Silica fume, a highly reactive pozzolan containing mostly amorphous silicon dioxide with particle sizes of about 150 nm, was added to improve microstructure of pores. Mixing and curing process involved use of drinking water conforming to requirements as per IS 456:2000.

3.2 Material Characterization

Physical properties of the constituent materials were evaluated before the manufacture of concrete mixes. Specific gravity of cement, aggregates, and other additives was assessed using relevant tests. The size distribution of the fine aggregate was evaluated using sieve analysis test according to the accepted procedure. For sieve analysis test, a specimen of 1000 grams of oven dried fine aggregate was sieved with respect to IS sieves. Percentage of aggregates retained on different sieves was used to calculate fineness modulus that was recorded as 2.51 which indicates that grading of fine aggregate satisfied Zone II grading. Specific gravity of cement was evaluated using pycnometer test and was found equal to 3.20.

The physical characteristics of the constituent materials utilized in this study are given in Table 1 and reflect the suitability of these materials for use in concrete manufacturing. The cement sample was found to have a specific gravity of 3.20, falling within the standard value range for OPC and reflecting its normal quality. The fine aggregate had a specific gravity of 2.60 and a fineness modulus of 2.51, belonging to Zone II grading and indicating proper grading for concrete purposes. The coarse aggregate had a specific gravity of 2.90 and a nominal maximum size of 20 mm. The quarry dust material made up of particles with dimensions less than 4.75 mm, possessing an angular shape and acting as a filler, was chosen as a fine aggregate substitute in the mixture. Silica fume had a specific gravity of 2.23 and an average particle size of about 150 nm.

Table 1. Physical Characteristics of Constituent Materials

Material	**Specific Gravity**	**Fineness Modulus**	**Remarks**
Cement (OPC 53)	3.20	–	Initial setting: 30 min; Final: 600 min
Fine aggregate	2.60	2.51	Zone II
Coarse aggregate	2.90	–	20 mm
Quarry dust	–	–	<4.75 mm
Silica fume	2.23	–	Particle size ~150 nm

3.3 Concrete Mix Proportioning

Mixes of concrete were prepared using M40 grade concrete mixes in accordance with IS norms with an objective to attain compressive strength of 48 MPa after 28 days curing period. The ratio of water/cement was kept constant at 0.43 in all specimens. Control specimen was prepared with cement, natural fine aggregate, crushed granite coarse aggregate, and water. Effects of waste material addition were analyzed by adding quarry dust replacing some of the fine aggregate while ceramic waste replaced some of the coarse aggregate. Further, silica fume was added as a supplementary cementitious material due to its capability in improving matrix densification and pozzolanic action. Proportions of different ingredients in the mix were fixed at the ratio of 1:1.12:2.30 (by weight). In order to analyze the effect on fresh and hardened properties, four different concrete mixes were produced which comprised of different proportions of silica fume, quarry dust, and ceramic waste; that is, 6%, 10%, and 10% silica fume, quarry dust, and ceramic waste respectively; 7%, 20%, and 20%; 8%, 30%, and 30%; 9%, 40%, and 40%.

Above Table 2 was analyzed to check the particle size distribution of the fine aggregate and determine the grade of the aggregate. The fine aggregate had a fairly distributed gradation on the sieve sizes. Its fineness modulus value was found to be 2.51, which means that the sand was of a medium grain nature. The result meets the requirement for Zone II fine aggregate, and shows that there is a good ratio between coarse and fine aggregates. The grading should make the concrete more workable, reduce segregation, and improve particle packing.

Table 2. Particle Size Distribution and Fineness Modulus of Fine Aggregate

IS Sieve Size	Weight Retained (g)	% Weight Retained	Cumulative % Retained
4.75 mm	8	0.8	0.8
2.36 mm	42	4.2	5.0
1.18 mm	215	21.5	26.5
600 µm	200	20.0	46.5
300 µm	310	31.0	77.5
150 µm	175	17.5	95.0
Pan	50	5.0	100.0
Total	**1000**	**–**	**251.3**

Fineness Modulus = 251.3 / 100 = 2.51

3.4 Specimen Preparation and Curing

The ingredients of concrete were mixed using the concrete mixer available in the laboratory to achieve a homogenous mixture. The fresh concrete was then poured into moulds in layers and compacted effectively to ensure there is no trapped air. Specimens in cube form of dimensions 150 mm × 150 mm × 150 mm were cast to test the compressive strength, while those of cylinder form having a diameter of 150 mm and a height of 300 mm were cast for split tensile strength. The specimens cast were then covered with plastic to prevent evaporation of water and removed from the moulds after 24 hours.

Table 3. Specific Gravity Determination of OPC Cement using Pycnometer Testing

Parameter	**Value**
Empty weight of bottle (W_1)	29.7 g
Weight of bottle + water (W_2)	161.0 g
Weight of bottle + kerosene (W_3)	115.7 g
Weight of bottle + kerosene + cement (W_4)	195.3 g
Weight of cement (W_5)	100.0 g

Specific gravity of kerosene (G_k) = (115.7 – 29.7) / (161 – 29.7) = 0.655

Specific gravity of cement (G) = (100 × 0.655) / (100 + 115.7 – 195.3) = 3.275 ≈ 3.2

The specific gravity of the cement sample was tested by means of pycnometer, and the resultant value was established to be 3.20, as can be seen in Table 3. Such a figure comes within the standard specific gravity values for OPC cement, which demonstrates normal density properties that can be used in concrete. The importance of knowing the specific gravity lies in the necessity to calculate the proportions properly. The result attained ensures the usability of the cement sample in M40 concrete class.

Material mass estimation is considered a basic requirement in concrete material characterization and proportioning. The digital balance depicted in Fig. 1 was used for weighing the various constituent materials used in the experiment. Accuracy of mass measurement is a prerequisite in the determination of some of the physical properties of concrete including its specific gravity. Using an accurate digital balance ensures that any errors in the measurements are reduced. This is critical in ensuring that the test outcomes are reliable and consistent. Cement, aggregate, quarry dust, ceramic waste, and supplementary cementitious materials should be accurately measured when conducting concrete experiments.

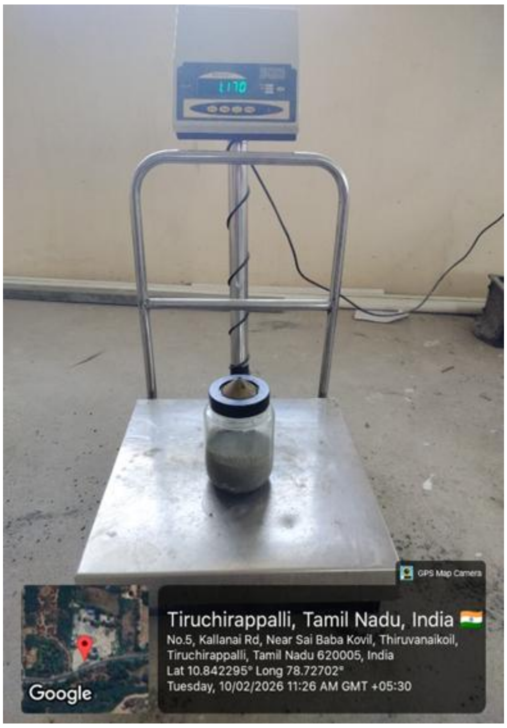

Figure 1. Digital Weighing Balance used for Material Characterization and Proportioning

3.5 Experimental Programme

Concrete mixtures' performance was tested by means of conducting fresh and hard concrete tests. Fresh concrete properties were determined from workability tests, which were conducted using the slump test. Compressive strength of the mixture was measured using the compression testing machine after curing at ages of 7, 14 and 28 days. Split tensile strength of the mixture was also tested using diametrical loading. The experimental program was formulated to investigate the effects of quarry dust, ceramic waste, and silica fume on the mechanical properties of M40 concrete.

The proportions of concrete mixes were calculated based on the M40 grade concrete with the water-cement ratio of 0.43. The reference concrete mix comprised 440.12 kg/m³ of cement, 585.37 kg/m³ of fine aggregates, 1191.48 kg/m³ of coarse aggregates, and 191.53 kg/m³ of water. Silica fume, quarry dust, and ceramic waste were added at different replacement rates to determine their impact on the concrete behavior. Four mixes were designed in which the silica fume percentage varied from 6% to 9%, whereas quarry dust and ceramic waste replacement rates were altered between 10% and 40%. The first mix included 6% silica fume, 10% quarry dust, and 10% ceramic waste, while the second mix included 7% silica fume, 20% quarry dust, and 20% ceramic waste. On the other hand, the third and fourth mixes involved 8% silica fume, 30% quarry dust, and 30% ceramic waste; and 9% silica fume, 40% quarry dust, and 40% ceramic waste, respectively. The chosen replacement rates are considered appropriate for investigating the collective impact of waste products on the fresh and hardened properties of concrete.

Table 4. Proportions of Experimental Concrete Mixtures

Mix	**SF (%)**	**QD (%)**	**CW (%)**	**Cement (kg)**	**Fine Agg. (kg)**	**Coarse Agg. (kg)**	**Water (kg)**
1	6	10	10	440.12	585.37	1191.48	191.53
2	7	20	20	440.12	585.37	1191.48	191.53
3	8	30	30	440.12	585.37	1191.48	191.53
4	9	40	40	440.12	585.37	1191.48	191.53

The concrete mixes were formulated to examine the joint impact of silica fume, quarry dust, and ceramic waste on the behavior of M40 grade concrete. As indicated in Table 4, the amount of cement, fine aggregate, coarse aggregate, and water remained unchanged during the experiment, but the amounts of silica fume, quarry dust, and ceramic waste were varied. The increasing levels of substitutions made possible the evaluation of material behavior at varying substitution levels, leading to the determination of the best mix proportion. This methodology allowed studying the effects of waste material use on concrete fresh and hardened state properties.

4. Testing Procedures

4.1 Compressive Strength Test

Compressive strength test is one of the key measures that can be employed to examine the ability of concrete to bear loads. Cube samples with dimension of 150mm × 150mm × 150mm were made for all the mix designs and cast as per testing requirements. Fresh concrete was poured into the molds in layers and compacted properly to avoid the presence of entrained air. The molds were then stripped off after 24 hours of pouring and subjected to water curing till the specified ages of 7, 14, and 28 days. The compressive strengths of concrete cubes were determined by means of calibrated compression testing machine (CTM). In this test, the load was applied uniformly on each sample until its failure, and the load carrying capacity was noted down. Compressive strengths were calculated by dividing the ultimate load by the loaded cross-section area of the cube. The test results were analyzed in order to study the effect of silica fume, quarry dust, and ceramic wastes on M40 concrete grade.

Figure 2. Compressive Failure of Concrete Cube Specimen During CTM Testing

Figure 2 presented above shows the failure mechanism of concrete cube when tested for compressive strength using a compression testing machine. It is noted that the concrete cube had some cracks and crush in the concrete material when subjected to high loads. This failure mechanism of concrete suggests the formation and expansion of internal stresses in the concrete sample. This provides useful information concerning the structural properties of the concrete mix. The compressive strength attained by the test was used to determine the effects of silica fume, quarry dust, and ceramics on the mechanical behavior of M40 concrete.

4.2 Split Tensile Strength Test

A split tensile strength test was carried out to investigate the resistance of concrete to tensile loads. This is a crucial factor since it is responsible for cracking of concrete in structures. Cylindrical concrete samples with diameters of 150 mm and heights of 300 mm were made using the conditions that prevailed when compressive tests were carried out. The samples were subjected to tests after the designated periods to assess the influence of waste materials on the tensile characteristics of concrete. In this case, a cylinder sample was put across the platens of the compression testing machine. Tension stress was created through a compressive force along the length of the cylinder sample. In this case, the compressive forces caused tension stress across the longitudinal axis. The maximum compressive load that led to failure was used in computing split tensile strength. The outcome of the experiment revealed the impact of quarry dust, ceramic wastes, and silica fume on the tensile properties of concrete mixtures.

5. Results and Discussion

5.1 Compressive Strength

Compressive tests carried out after seven days, fourteen days, and twenty-eight days showed the effect of silica fume, quarry dust, and ceramic waste on the strength development of M40-grade concrete. Generally, there was an improvement in strength with an increase in curing age because of continued hydration and densification of the cement paste. The mixture of 6% silica fume, 10% quarry dust, and 10% ceramic waste produced the highest compressive strength of 53.33MPa at the age of 28 days. This result was possible due to the packing effect and pozzolanic action where the quarry dust packed the cement matrix while silica fume reacted with the calcium hydroxide to form additional C-S-H gel. However, high strength was not attained with a higher amount of replacements because excess quarry dust and ceramic waste may have increased the water demand hence making the concrete weak and with a lot of holes in it. There was also a possibility of affecting the aggregate structure.

The compressive strength values attained for different ages of curing are provided in Table 5. An increasing trend in the strength values was noticed in all types of concrete mixes with the increase in curing age, showing hydration of cement along with matrix formation. Out of the various mixtures considered for study, the 28-day compressive strength of Mix1 was found to be highest at 53.33 MPa, which was greater than the required compressive strength for M40 concrete. This can be attributed to the good packing of particles due to quarry dust and refined structure owing to silica fume. Although there was an increase in strength in all the mixes, a decline in strength value was witnessed for increasing replacement levels. This indicates that excess inclusion of quarry dust and ceramic waste may result in a negative impact on matrix integrity and bond between aggregates and paste.

Table 5. Compressive Strength of Concrete Mixtures at Various Curing Ages

Mix	SF :QD : CW (%)	7 days	14 days	28 days
1	6 :10 : 10	35.0	40.0	53.33
2	7 :20 : 20	35.0	37.0	45
3	8 :30 : 30	35.0	37.78	40
4	9 :40 : 40	35.0	40.0	45

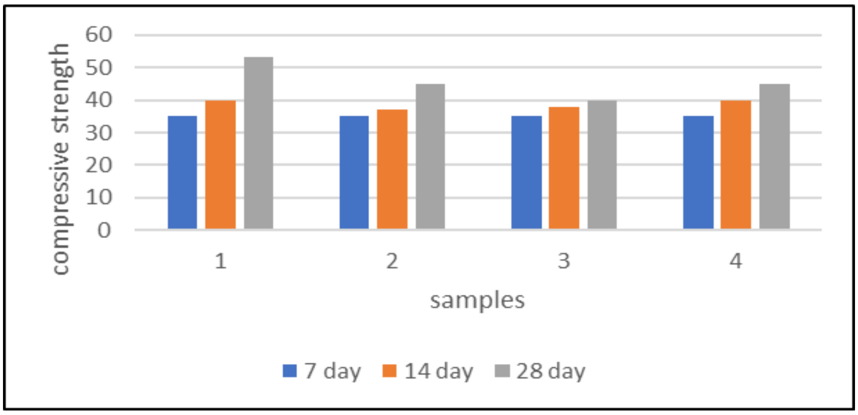

Figure 3. Effect of Curing Age on Split Tensile Strength of Concrete Mixtures

Fig. 3 shows the variation of compressive strength as a function of curing time for all the tested concrete mixes. It can be seen from the figure that the increasing strength with age trend between 7 days and 28 days has been well captured in all the replacement ratios. This is because of increased hydration reactions and progressive densification of the concrete microstructure due to the curing period. Mix 1 attained the highest compressive strength after 28 days of curing, meaning that moderate replacement percentages of quarry dust and ceramic waste can improve the mechanical performance of concrete. The relatively low strengths obtained at high replacement rates could be due to the formation of porosity, higher water requirement, and inefficient aggregate-matrix bonding.

5.2 Split Tensile Strength

The results of the split tensile strength show an increasing trend in the tensile strength due to the continuous process of hydration and densification of the microstructure. Split tensile strength at 28 days is greater than the split tensile strength at 7 and 14 days. It is due to the beneficial effect of curing on crack resistance and stress transfer in concrete. In comparison with other mixes, Mix 3 had the highest value of split tensile strength at each age of curing. An improvement in the properties of mix 3 was caused by the angular shape and surface roughness of quarry dust and ceramic waste aggregates, which allow mechanical interlocking between aggregates and paste. In addition, the use of silica fume leads to a refined transition zone where the microcracks do not occur under tensile loads. It should be mentioned that the application of quarry dust, ceramic waste, and silica fume improves the crack resistance of concrete without decreasing its strength.

Table 6. Split Tensile Strength Results (MPa)

Curing Period (days)	Mix 1 (10% SF + 10% QD + 10% CW)	Mix 2 (7% SF + 20% QD + 20% CW)	Mix 3 (8% SF + 30% QD + 30% CW)
7	2.48	3.05	3.61
14	2.62	3.19	3.82
28	2.76	3.33	4.03

The results of split tensile strength values at various curing ages are shown in Table 6. It is evident from the findings that there was an increase in tensile strength as the curing age increased in all the concrete mixes because of the progressive hydration process and the development of bonds between the matrix and aggregate particles. The concrete mix that registered the highest tensile strength was Mix 3, which had a maximum value of 4.03 MPa after 28 days. The improved tensile behavior of concrete is due to the rough surface of quarry dust and ceramic waste particles, which improved mechanical bonding between the aggregates and the matrix, thus promoting stress transfer. Additionally, the use of silica fume ensured that the interfacial transition zone was well-refined, resulting in fewer micro-cracks.

The variation in split tensile strength with respect to curing age is depicted in Fig. 4. It was noted that there is a uniform increase in tensile strength with time from 7 days to 28 days, which is attributed to the continuous hardening process of the cement paste and better bonding between aggregates and paste. It is evident from the graph that the trend in tensile strength is directly proportional to the percentage of replacement in the range of investigations performed, and Mix 3 showed the best results in terms of performance. The trend witnessed in Fig. 4 is indicative of the potentiality of the used wastes in developing concrete with good tensile strength.

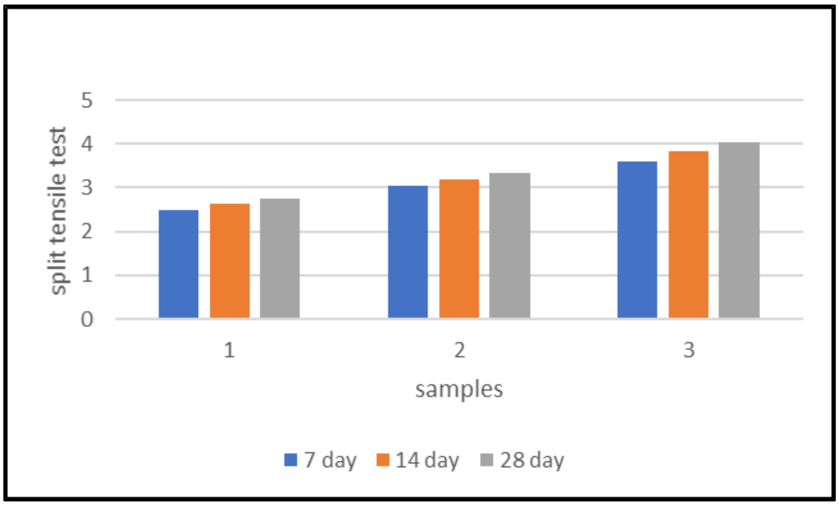

Figure 4. Effect of Curing Age on Split Tensile Strength of Concrete Mixture

5.3 Discussion

The mechanical behavior of the investigated concrete mixtures depended on parameters like particle packing, microstructure densification, and bond between aggregate and matrix. The inclusion of quarry dust acted as a filler, which enhanced particle packing and minimized connectivity of pores, resulting in higher compressive strength at moderate amounts of replacement. The silica fume was important in modifying the microstructure of the concrete through the filling and pozzolanic reactions. The very fine particles were involved in sealing the capillary pores to refine their structure, and the reaction of the silica fume with calcium hydroxide helped in creating dense calcium silicate hydrate gel. The use of ceramic waste provided angular and coarse surface particles for mechanical interlocking; however, too high of replacement might have resulted in high porosity and higher water requirement. Thus, the replacement amount needs to be optimized in order to get the balance between sustainability and mechanical performance. The research indicated that the use of quarry dust, ceramic waste, and silica fume resulted in concrete with satisfactory mechanical strength.

6. Conclusion

The results of the experimental study indicated that the use of quarry dust and ceramic waste as a replacement material for natural fine and coarse aggregate in the production of silica fume concrete grade M40 is possible. An increase in compressive and splitting tensile strength of concrete mixtures with increased age of their curing proved the effectiveness of strength development. Out of all the mixes examined, those made with a combination of 6% silica fume, 10% quarry dust, and 10% ceramic waste showed the highest 28-day compressive strength (53.33 MPa), while the mixture with 8% silica fume, 30% quarry dust, and 30% ceramic waste exhibited the highest splitting tensile strength (4.03 MPa). Such an improvement in concrete properties can be attributed to increased particle packing, matrix densification, and pozzolanic reaction of silica fume. It can be concluded that quarry dust and ceramic waste can be used in concrete manufacturing and thus contribute to sustainable development via reducing the exploitation of natural materials.

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