Evaluation of the relationship between strength, quality grade, microstructure and abrasion of concrete

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Abstract
Surface abrasion is the most general cause of concrete deterioration. Abrasion can be a catalyst for structural failures, as abrasion leads to structural cracks and reinforcement corrosion. The abrasion of the concrete surface is a reflection of the compressive strength and quality grading of the concrete. This study aims to examine the relationship between abrasion, compressive strength, and quality grading of concrete. The mechanical properties, quality grading, and abrasion of the concrete were evaluated based on the compressive strength (IS 516), ultrasonic pulse velocity (IS 13311), and sandblasting abrasion testing (IS 9284), respectively. Abrasion resistance increased with compressive strength and ultrasonic pulse velocity. The study was supported by microstructural analysis and surface chemical composition of the concrete. It was concluded that quality grading, sound microstructure, and abrasion resistant concrete with higher compressive strength along with the use of superplasticiser leads to better abrasion resistance.

1. Introduction

Concrete, a construction material, is a proportionate mixture of cement, aggregates, water, and admixtures. Delivering the desired quality of concrete is an essential part of the construction industry. Despite several innovations in concrete technology, the quality of concrete is most commonly represented by its compressive strength. In addition, the mechanical properties and durability of the concrete are also used as indicators to determine its quality [1].

The cross-section of the concrete is divided into two parts: heartcrete and covercrete, as shown in figure 1. Heartcrete is the concrete mass accumulated in the reinforcement that is responsible for the mechanical properties of the concrete such as compressive strength, tensile strength, and flexural strength. Covercrete represents the upper layer of the concrete from the reinforcement to the surface; covercrete is responsible for the durability properties of the concrete like abrasion, ion penetration, electric resistivity, and acid attack resistance [2]. Deterioration in the covercrete properties of concrete leads to weakness of the concrete surface, which ultimately affects the mechanical properties of the concrete [3]. Though authors have investigated the durability (electrical resistivity) properties and compressive strength of the concrete, the exact correlation between the compressive strength and the cement type could not be established. Nevertheless, it was found that the surface resistivity, indicated by resistance to chlorine penetration by the surface, affects the strength of the concrete. Specifically, surface resistivity was found to increase with an increase in the compressive strength [3]. Ultrasonic Pulse Velocity (UPV) can be used to define the quality of concrete as per IS 13311 part 1 [4]. Experimental observations showed that the ultrasonic pulse velocity increases steeply in the early age of concrete (i.e. 16 h to 72 h), followed by a slow increase up to 120 h. Another study postulated that UPV does not drastically increase till 672 h as filling of pours and reducing the gap starts at the early stage of concrete. Linear regression equation was used to correlate UPV with the compressive strength. The Linear regression equation thus formulated was then used to determine the compressive strength of the concrete given the UPV values [5].

Coarse aggregates influence the ultrasonic pulse velocity and ultimately affect the compressive strength of the concrete. Al-Numan et al studied the effect of density of the coarse aggregates on the compressive strength of the concrete using UPV measurements and found slight variations in the compressive strength as the density of the coarse aggregates was varied between 1100 kg m\(^{-3}\) and 1400 kg m\(^{-3}\) [6]. Abrasion resistance of the concrete depends on the
material selection, mix proportion, and compressive strength [7–9]. Researchers have observed that abrasion resistance increases with increase in the compressive strength for all types of aggregates; specifically, abrasion resistance increased if hematite was used as coarse aggregate [10]. As the concrete material’s abrasion resistance depends on the concrete production process, establishing a correlation between abrasion resistance and compressive strength is challenging [7]. Reports point out that concrete incorporated with nanoparticles exhibits higher abrasion resistant surface than the cement mortar without nano ingredients. Wang et al. found that nano Silica (SiO2) blended with 1% to 3% weight of cement and cured at room temperature exhibited an abrasion loss of about 0.38 kg m⁻² to 0.50 kg m⁻² with an absolute decrease in abrasion loss from about 0.25 kg m⁻² to 0.13 kg m⁻². Similarly, addition of 1% to 3% Nano-TiO2 and Nano-ZrO2 to the concrete reduced abrasion from 0.44 kg m⁻² to 0.43 kg m⁻² and 0.42 kg m⁻² to 0.14 kg m⁻², respectively. These observations indicate that the addition of nanomaterials in specified quantity is effective in enhancing the abrasion resistance of the cement mortar. On the other hand, the compressive strength of the cement mortar cured for 28 days was found to be about 48% higher than that of the control cement mortar [11, 12]. Thus, it can be concluded that the introduction of nanomaterials such as Graphene, SiO2, TiO2, and ZrO2 increases both, the abrasion resistance and the compressive strength of the concrete [12].

This study investigates and correlates the mechanical properties and durability properties of the concrete with its compressive strength. It is to be noted that since the abrasive and environmental forces affect the concrete surface, the effective maintenance of concrete pavement requires regular monitoring of conditions and strength of the concrete by employing simple methods. Non-destructive tests offer the advantage of determining concrete properties such as density, pore presence, and surface hardness. Furthermore, the compressive strength of the concrete plays a vital role in deciding the adequacy of strength at the time of production or even at later services, which is very desirable as it helps to ascertain the serviceability or durability. As abrasion properties of the concrete are influenced by its compressive strength, in the present work, the effect of compressive strength and surface microstructure on the abrasion of the concrete is investigated. Further, the effect of compressive strength on UPV and abrasion resistance is also studied. On the whole, this study aims to provide a comprehensive understanding of the effect of compressive strength on the serviceability or durability of the concrete.

2. Experimental procedure

2.1. Materials and mix design

Ordinary Portland Cement of 53 grade, with specific gravity 3.15, fineness below 10%, and normal consistency 32% was used in this research [13]. Natural river sand confirming to zone II and coarse aggregate of 20 mm nominal maximum size derived from stone crushing were used in this study [14]. Physical properties of the ingredients were studied for mix design as per IS10262, and are shown in table 1.

The mix was designed for M20, M25, M30, M35, and M40 grades as per IS 10262:2000 [20]. In addition, design stipulations that include a good degree of supervision, concrete in mild exposure and 50 mm slump value of workability in direct placing conditions were adopted to design the concrete mix. Mix proportions for various grades of concrete are shown in table 2.
Table 2. Mix proportions of the concrete (ingredient content for 1 m³).

| Sample | Targeted strength (N mm⁻²) | Proportion  | Cement (Kg) | w/c  | Water content (Kg) | Fine aggregate (Kg) | Coarse aggregate (Kg) | Remark                  |
|--------|-----------------------------|-------------|-------------|------|-------------------|---------------------|-----------------------|-------------------------|
| S1     | 20                          | 1:2.32:3.75 | 325         | 0.46 | 149.5             | 756.08              | 1219.68               |                         |
| S2     | 25                          | 1:1.75:2.90 | 320         | 0.43 | 138               | 751                 | 1356                  |                         |
| S3     | 30                          | 1:1.75:2.86 | 387.5       | 0.48 | 186               | 680                 | 1110                  |                         |
| S4     | 35                          | 1:2.43:3.02 | 350         | 0.44 | 154               | 864                 | 1059                  | Admixture (superplasticizer) used. |
| S5     | 40                          | 1:2.16:2.75 | 385         | 0.4  | 154               | 834                 | 1060                  | Admixture (superplasticizer) used. |
2.2. Test specimen and procedure
Tests to determine the compressive strength were performed on 150 mm cube after 28 days of curing, to ensure that the targeted strength of the mix has been achieved. The flexural strength and split tensile strength tests were conducted on 700 mm × 150 mm × 150 mm beam and 150 mm × 300 mm height cylinder, respectively, to compare the performance of the mix grade with the compressive strength. The test specimens were cast and tested according to Indian Standards.

Three concrete specimens for each of the mixes were subjected to compressive, flexural, and split tensile strength tests at 28 days. Compressive strength and split tensile strength tests were carried out using a compressive testing machine of 100 tonnes capacity, while the flexural strength test was carried on a universal testing machine of 200 tonnes capacity. The load was applied axially on the specimen in a gradual manner without shock until the specimen cracked and was crushed. The specimen that underwent flexural test resisted the failure during bending when a single point load was applied. Split tensile strength was conducted as per the IS 5816–1999 (reaffirmed 2004) without shock as the load was increased continuously at the rate of 1.2 N mm\(^{-2}\) min\(^{-1}\) to 2.4 N mm\(^{-2}\) min\(^{-1}\).

The quality of the concrete in terms of density, homogeneity and uniformity were examined by Ultrasonic Pulse Velocity Test as per IS 13311. The ultrasonic pulse generated by an electro-acoustic transducer undergoes multiple reflections at the boundaries of the concrete specimen. The pulse generated is independent of the geometry of the concrete through which it passes, and depends only on the elastic properties of the concrete. Higher velocities are observed when the quality of the concrete in terms of density, homogeneity and uniformity is good. Tests were conducted on three slab specimens of dimension 300 mm × 300 mm × 100 mm by passing 150 kHz natural frequency through the 300 mm path length. The pulse velocities were recorded for further analysis of the quality of the concrete.

Abrasion resistance of the concrete is a measure of the durability and deterioration of the concrete surface due to forces applied on the surface. The abrasion test inline with IS 9284 provides information on the potential applicability of the concrete for a particular concrete structure. Since deterioration leads to weaker upper surface of the concrete, all tests were conducted on three concrete cubes of size 100 mm for all mixes in order to have statistically consistent results. The surface of the 100 mm cube was subjected to the abrasive charge of sand, which is in conformity with the IS 650 (i.e. graded to pass 1.00 mm IS sieve and retained on 0.50 mm IS sieve). Loss of mass for each of the four surfaces of the cube was noted after the surfaces were applied with 4000 grams abrasive charge driven at an air pressure of 0.14 N mm\(^{-2}\). In addition, the four surfaces of each cube were tested twice with 1800 changed orientation and inclinations during sandblasting by the cradle.

3. Results and discussion
This study is intended to find the effect of compressive strength on the abrasion and UPV properties of the concrete mixes namely, M20, M25, M30, M35, and M40. Thus, it is necessary to understand the flexural and tensile behaviour of the concrete under loading before correlating the compressive strength with the durability properties. Figure 2 shows the compressive strength, flexural strength and split tensile strength for the concrete mixes. Compressive strength and flexural strength strongly influence the concrete structures and are related as per IS 456, i.e., Flexural strength = 0.7 × \(\sqrt{\text{Compressive Strength}}\). Figure 2 shows that the flexural
strength and tensile strength of the selected grade of concrete gradually increase with increased compressive strength.

The ultrasonic pulse velocity test results show that the concrete possesses excellent quality grading in line with the requirements of IS 13311. The UPV values plotted for various concrete mixes are shown in figure 3 indicates that M20, M25, & M30 grade concrete fall in the category of good concrete grading, while M35 and M40 fall under the excellent concrete grading category. It was observed from the microstructure image in figure 4(a) and the element distribution analysis in figure 4(b) that the M40 grade of concrete is denser. Addition
of superplasticiser enhances the workability of the concrete even with reduced water content. This reduction in water consequently improves the strength of the concrete which in turn influences the abrasion property of the concrete. It was found that UPV as a function of the compressive strength can be represented by the cubic curve equation (1) with a coefficient of determination of 0.952,

\[ x = 194.1 - 12.74y + 0.2817y^2 - 0.002051y^3 \] (1)

Here, \( x \) is the average pulse velocity (km s\(^{-1}\)) and \( y \) is the compressive strength (kN mm\(^{-2}\)).

Ultrasound pulse velocity test categorizes the concrete grading as good and excellent in terms of the uniformity and density of the concrete for selected concrete mixes, as shown in figure 3. It is necessary to evaluate the properties of the surface on which the external forces act. Surface microstructure of M25 grade of concrete presented in figure 5(a) shows that the surface is uniform. Figure 5(b) represents the EDS analysis of M25 grade concrete that depicts the chemical distribution within the concrete. The EDS of the surface shows equal distribution of all elements on the surface (see figure 5(b)). Pores present on the surface are due to the heat released during hydration. These hydration based pores weaken the concrete surface which in turn lowers the surface properties such as quality grade and abrasion comparatively as observed in figure 3 and table 3, respectively. Further, silicate in the concrete gives hardness to the concrete surface due to its higher compressive strength. Thus, silicate-based compounds can be used as surface hardeners wherever required.

Next, the abrasion resistance was analysed with respect to compressive strength. It was observed that the percentage loss of weight due to abrasion decreases with increase in compressive strength. The average percentage loss for three specimens each of M20, M25, M30, M35, and M40 was found to be 0.25, 0.23, 0.23, 0.22, and 0.19, respectively. The abrasion losses for various mixes are shown in table 3. The concrete produced with this mix can be used for the concrete pavement for pneumatic tyred traffic only, railway platform and footpaths while being restricted to the concrete pavement with mixed traffic including iron tyred traffic, factory floors and dockyards in line with the requirements of IS 9284[2]. The relation between compressive strength and the percentage loss of weight due to abrasion for various mixes is shown in figure 6.
Table 3. Abrasion loss of concrete specimens.

| Grade of concrete | Specimen | Initial weight (in gm) | 0° | 180° | % loss | 0° | 180° | % loss | 0° | 180° | % loss | 0° | 180° | % loss | Average percentage loss |
|-------------------|----------|------------------------|----|------|--------|----|------|--------|----|------|--------|----|------|--------|-------------------------|
| M20               | 1        | 2716                   | 2712 | 2709.2 | 0.25 | 2705.1 | 2702.4 | 0.25 | 2698.6 | 2695.1 | 0.27 | 2691.8 | 2688.9 | 0.23 | 0.25 |
|                   | 2        | 2617.0                 | 2628.2 | 2625.1 | 0.25 | 2621.5 | 2618.3 | 0.26 | 2615.1 | 2612.2 | 0.23 | 2608.3 | 2605.6 | 0.25 |
|                   | 3        | 2777.89                | 2774.4 | 2770.5 | 0.27 | 2766.3 | 2762.7 | 0.28 | 2759.1 | 2756.8 | 0.21 | 2752.7 | 2749.8 | 0.25 |
| M25               | 1        | 2668.6                 | 2665.7 | 2663.2 | 0.20 | 2661.3 | 2658.09 | 0.18 | 2653.1 | 2649.2 | 0.23 | 2645.3 | 2641.2 | 0.30 | 0.23 |
|                   | 2        | 2780.9                 | 2777.8 | 2775.1 | 0.21 | 2772.3 | 2769.1 | 0.22 | 2765.6 | 2761.7 | 0.24 | 2757.6 | 2754.5 | 0.26 |
|                   | 3        | 2824.9                 | 2821.6 | 2818.3 | 0.23 | 2815.5 | 2812.7 | 0.20 | 2808.2 | 2804.6 | 0.23 | 2800.1 | 2797.2 | 0.26 |
| M30               | 1        | 2696.6                 | 2693 | 2689.2 | 0.23 | 2686.2 | 2682.1 | 0.22 | 2679.4 | 2675.8 | 0.21 | 2671.3 | 2668.3 | 0.28 |
|                   | 2        | 2624                  | 2620.3 | 2617.5 | 0.25 | 2614.6 | 2611.7 | 0.22 | 2608.3 | 2603.2 | 0.26 | 2600.1 | 2597.3 | 0.23 |
|                   | 3        | 2681                  | 2677.9 | 2673.4 | 0.23 | 2670.1 | 2667.3 | 0.23 | 2664.8 | 2661.2 | 0.23 | 2658.4 | 2655.1 | 0.23 |
| M35               | 1        | 2678.5                 | 2675.1 | 2672.7 | 0.22 | 2669.9 | 2666.7 | 0.22 | 2664.5 | 2662.6 | 0.15 | 2659.2 | 2656.9 | 0.21 |
|                   | 2        | 2630.7                | 2627.5 | 2624.1 | 0.25 | 2621.6 | 2619.7 | 0.21 | 2616.4 | 2613.8 | 0.23 | 2610.5 | 2607.1 | 0.26 |
|                   | 3        | 2715.6                | 2712.1 | 2709.8 | 0.23 | 2707.2 | 2704.5 | 0.20 | 2701.6 | 2698.7 | 0.21 | 2695.9 | 2693.1 | 0.21 |
| M40               | 1        | 2659.4                | 2656.8 | 2654.1 | 0.20 | 2653.9 | 2649.2 | 0.19 | 2646.9 | 2644.1 | 0.19 | 2641.5 | 2639.0 | 0.19 |
|                   | 2        | 2891.2                | 2888.2 | 2885.9 | 0.19 | 2883.8 | 2881.7 | 0.18 | 2878.9 | 2875.8 | 0.20 | 2873.1 | 2871.9 | 0.14 |
|                   | 3        | 2732.1                | 2729.9 | 2727.2 | 0.18 | 2725.1 | 2723 | 0.18 | 2721.4 | 2718.9 | 0.18 | 2716.2 | 2713.5 | 0.20 |
and percentage loss in weight of the concrete is obtained by plotting compressive strength on the abscissa and percentage abrasion loss on the ordinate as shown in figure 6. The mathematical relation between the two follows equation (2) given below.

\[
AL = 7.194 - 0.4637y + 0.01029y^2 - 0.000076y^3
\]

(2)

where, \(AL\) is the percentage abrasion loss, and \(y\) is the compressive strength (kN mm\(^{-2}\)).

Figure 7 shows the ultrasonic pulse velocity (Km s\(^{-1}\)) and average percent abrasion loss as a function of the grade of concrete. It is evident that increase in the quality of concrete improves the abrasion resistance of the concrete surface. Moreover, increase in the pulse velocity and compressive strength indicates that the concrete surface has better abrasion resistance. Thus, it is clear that the compressive strength influences the quality grading and abrasion properties of the concrete.

### 4. Conclusion

Experiments were conducted to study the effect of compressive strength on the abrasion resistance and ultrasonic pulse velocity of different grades of concrete. The following conclusions were drawn from this study:

- The quality grade of the concrete assessed in terms of UPV shows that the UPV increases with increase in the compressive strength. Equation (1) provides the correlation between UPV and compressive strength that helps to find out the applicability of the concrete whenever needed.
The concrete grades used for the testing can be used as concrete pavement for pneumatic tyred traffic. In addition, equal distribution of chemical constituents helps to achieve better abrasion resistant concrete surface.

Abrasion resistant property of the concrete depends upon the compressive strength and the surface microstructure; abrasion resistance increases with increase in compressive strength and can be determined by equation (2).

Abrasion resistance also depends on the quality grades; abrasion resistance increases with increase in the ultrasonic pulse velocity.

The concrete grades used for the testing can be used as concrete pavement for pneumatic tyred traffic only, in railway platform and in footpaths but restricted to the concrete pavement with mixed traffic, including iron tyred traffic, factory floors, and dockyards to produce a denser concrete surface with limiting abrasion loss up to 0.16.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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