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Role of crumb tyre aggregates in rubberised concrete contained granulated blast-furnace slag

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Abstract. Wise management of waste materials can be quite intensive in terms of ecological friendliness and human safety. Proper recycling of industrial wastes can lead to immense practical benefits. This paper determines the feasibility of improving the properties of concrete by incorporating waste tyre aggregates (TAs) and ground granulated blast-furnace slag (GGBFS) at varied percentages. Construction applications of rubberised concrete (RC) is limited due to presence of weak bonds between the cement paste and rubber lumps. The size and hardness of the rubber aggregates in RC make its compressive strength lower compared to traditional one. To overcome such shortcomings, GGBFS was included. Furthermore, crumb TAs of two different size distributions (fine lumps of size range 1 to 4 mm and coarse piles of sizes within 5 to 8 mm) at varied levels (5, 10, 20 and 30% of volume) were used to replace GGBFS addition to concrete. Three groups of concrete specimens were prepared, first group using TAs (size 1 to 4 mm) as partially replaced fine aggregates, second group using TAs (size 5 to 8 mm) as partly replaced coarse aggregates and the last group partially replaced both TAs. Next, GGBFS of 20% as partial replacement of cement was admixed to all groups and compared with the control mix. Workability and mechanical properties of the designed mixes were evaluated in terms of slump and compacting factor, compressive, flexural and tensile strengths, and modulus of elasticity. Specimens containing GGBFS revealed improved mechanical behaviour. Meanwhile, the compressive strength of OPC specimen (after 3 months of curing) was 37.17 MPa. Moreover, specimen mixed with 5% of TA as replacement of coarse aggregates and 20% of GGBFS was almost 6% higher than the OPC specimens (39.54 MPa). It was concluded that recycled TAs as waste material could potentially be combined with GGBFS to attain high strength RC, constituting a novel strategy with immeasurable environmental, technological and economic benefits.

1. Introduction

Annually, approximately 1 billion tyres are utilized and end their service life worldwide wherein above 50% of them is abandoned in the landfills as scrap with no treatment [1]. An estimate revealed that by the end of 2030 about 5 billion tyres that would be dumped as wastes into landfills are going to be a major environmental concern unless inhibited [2]. In this spirit, recycling of such easily accessible and cheap product for making some useful construction materials has emerged as a suitable alternative [3]. This will not only contribute to the remedial measure towards environmental pollution but also make certain new construction materials economic and plentiful.

Recent literature hinted that in the USA due to the innovative reuse of waste tyre aggregates (TAs) in the civil engineering sector its amount has been dropped from 639.99 thousand tons in 2005 to 172 thousand tons in 2013 (about 73.12% reduction) [4]. This data clearly indicates that the demand of using waste tyres for constructional applications has been enhanced. Thus, intensive research efforts have been made to develop environmental friendly processes for the proper exploitation of discarded tyres instead of simply dumping them in the landfill to cause pollution [2].

Mohammadi et al. [5] acknowledged that the workability, setting time, segregation and bleeding of concrete could reduce with increasing rubber TAs content. Crumb rubber with lump sizes in the range of 0.425 to 4.75 mm as partial replacement to fine aggregates (natural sand) in concrete can reduce the workability substantially [6, 7, 8, 9]. On the contrary, some other reports displayed an increase in the workability due to partial replacement of the fine aggregates by crumb rubber piles [10, 11, 12]. Compressive strength of concrete has been shown to reduce with the increase in the porosity and decrease in the TAs gradation coarseness [13]. Incorporation of 10% crumb rubber (by volume) having lump size ranged from 1 to 5 mm was found to reduce the compressive and flexural strength from 5.73% to 29.47%, respectively [14].

Over the years, it has been established that rubber aggregates affect negatively the compressive strengths, flexural strengths and static elastic modulus of concrete. Overall mechanical characteristics have been shown to reduce considerably with the increase in TAs content as replacement. This observation was majorly attributed to the large discrepancy between the elastic modulus of TAs and hardened cement paste as well as poor growth of transition zone interfaces [15]. Besides, crumb rubber after soaked in water exhibited higher strength than without any water treatment [5]. The mechanical attributes were found to deteriorate with the incorporation of crumb rubber lumps with the size range of 2 to 6 mm as partial substitute to traditional fine aggregates [16]. Some studies recommended for partial substitution of cement with silica fume to diminish the deterioration in the compressive and flexural strengths of concrete that occurred due to inclusion of TAs [17].

Rubber TAs inclusion mediated reduction in the concrete strength was primarily ascribed to three mechanisms. Firstly, the deformation of the rubber lumps inside the concrete that could initiate the cracks formation in their neighbourhood. Secondly, the formation of weak bonds among the cement paste and rubber lumps. Lastly, the rubber aggregates density, morphology (size and shape) and hardness could be decisive factors in determining the concrete strength. Thus, incorporation of rubber TAs as a substitute to the natural fine aggregates could be responsible for the reduction of concrete strength [6]. Despite many efforts of using waste TAs in concrete to modify its strength and to achieve more cost effective as well as environmental friendly construction materials, the role of rubber aggregates in improving the mechanical properties of concrete is far from being understood.

This study took an attempt to determine the role played by waste TAs when incorporated in concrete as partial replacement to GGBFS. Concrete specimens with varied predefined ratios of TAs and GGBFS were designed. Performances of the prepared concrete specimens (fresh and hardened) were evaluated and compared with the control mix. As prepared concrete specimens were characterized using several tests to determine properties such as slump, compressive strength, compactness, flexural and tensile strength, and elastic modulus.

2. Materials and Methods

2.1 Tire Aggregates

Considering the significant effects of TAs on the compressive strength of concrete, present study incorporated them as alternative agent to design new concrete mixes. Thus, TAs with varied percentages (5%, 10%, 20% and 30% by volume) of NA (natural sand) was used to achieve rubberised concretes (RCs). The TA was procured from the Yong Fong rubber industries Sdn. Bhd. (Malaysia). Two types of TAs with granular sizes from 1 to 4 mm (called fine aggregates) and from 5 to 8 mm (called coarse aggregates) were used as raw materials (Figure 1). ASTM C136 method was used to grade these TAs. Table 1 and Table 2 enlist the chemical composition and physical properties of the used rubber TAs, respectively, sourced by Yong Fong rubber industries Sdn.

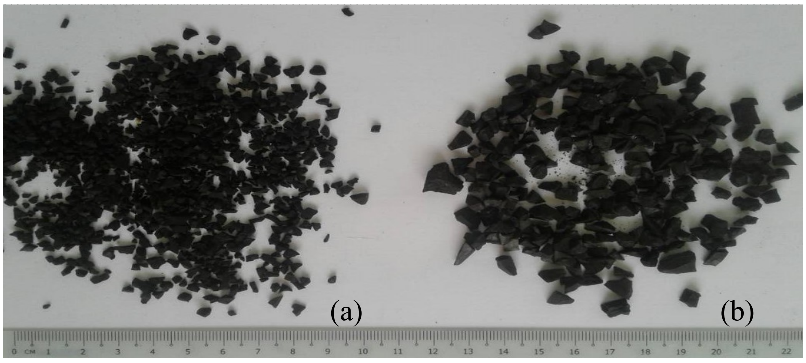

Figure 1. Crumb rubber TAs showing two different size distributions in the range of (a) 1–4 mm and (b) 5–8 mm.

Table 1. Chemical constituents of rubber aggregates.

Chemical Composition	Values (%)
Acetone Extract (ISO 1407)	10 ± 3
Ash Content (ISO 247)	24 ± 3
Carbon Black (ISO 1408)	14 ± 8
Rubber Hydrocarbon (RHC) by difference	52 ± 5

Table 2. Physical properties of TAs

Physical Properties	Unit	Values
Size (ASTM D5644)	mm	1 to 4 & 5 to 8
Heat Loss (ASTM D1509)	kgf/cm2	<1%
Metal Content (ASTM D5603)	%	<0.5%
Fiber Content (ASTM D5603)	ML (Vr)	<1%

2.2 Ground Granulated Blast Furnace Slag (GGBFS)

In this work GGBFS, a by-product produced by iron and steel making industries in Johor (Malaysia) was used. It was utilized in concrete to partially replace the ordinary Portland cement (OPC). Table 3 enlists the chemical composition of GGBFS and OPC, obtained from X-Ray Fluorescence test (XRF).

Table 3. Chemical composition of GGBFS and OPC obtained from (XRF) test

Chemical Compounds	Concentration	
	OPC (%)	GGBS (%)
Silica (SiO2)	17.60	33.70
Aluminium oxide (Al2O3)	4.53	14.29
Iron (III) oxide (Fe2O3)	3.35	0.39
Calcium oxide (CaO)	67.84	44.17
Magnesium oxide (MgO)	2.18	0.47

Potassium oxide (K2O)	0.27	0.33
Loss on ignition	1.73	1.46

2.3 Fine and Coarse Aggregates

Generally, the aggregates of concrete mix constitute 60 to 80% of the total volume in which the maximum size of sand particles used as a fine aggregate is ≈ 4.75 mm (sieve #4) and for coarse aggregate such as crushed stone gravel the highest size is ≈10 mm. Table 4 summarizes some physical properties of typical fine and coarse aggregates utilized in concretes. Figure 2(a) and (b) show the results on sizes of granular rubber lumps obtained from sieve test for fine (1-4 mm) and coarse (5-8 mm) aggregates.

Table 4. Physical characteristics of fine and coarse and granular rubber Aggregates.

Material	Water Absorption (%)	Specific Gravity	Maximum Size (mm)
Fine aggregate	2.2	2.65	4.75
Coarse aggregate	1.2	2.67	10
Granular rubber (1-4 mm)	-	1.34	4
Granular rubber (5-8 mm)	-	1.37	8

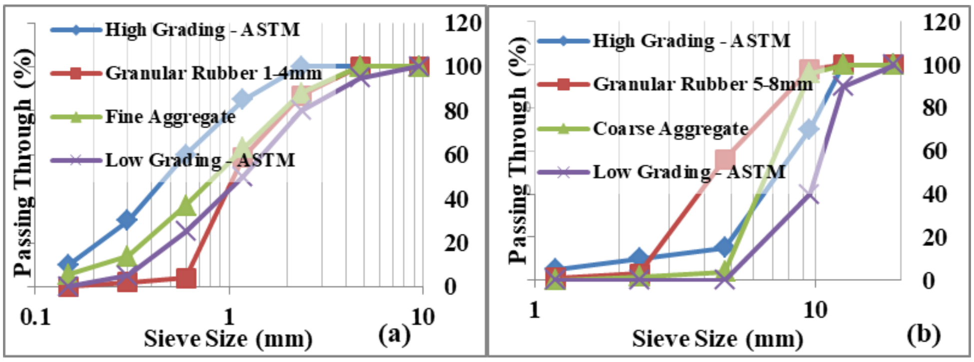

Figure 2. Sieve analysis of rubber TAs (a) fine grain of size 1 to 4 mm and (b) coarse lumps of size 5-8 mm.

3. Design of Concrete Mixes and Tests Program

3.1 Preparation of Concrete Specimens

The concrete mixes were designed in accordance to BS 5328-97 standard with water-cement (w/c) ratio of 0.55. The compressive strength of the designed mixes was targeted from 30 to 40 MPa with an effective workability in the range of 30 to 60 mm. Several batches of concrete mixes was achieved with 20% of GGBFS as cement replacement and different amount of rubber aggregates substituent (fine and coarse aggregates) as summarized in Table 5.

Table 5. Mix proportions of the designed concrete mixes at fixed w:c = 0.55.

Mix	Cement (kg/m3)	GGBFS (kg/m3)	TAs (%) of NA volume		Fine TAs (kg/m3)	Coarse TAs (kg/m3)
			1-4 mm	5-8 mm		
OPC	419	-	-	-	721	995
C	335.2	83.8	-	-	721	995
RF5	335.2	83.8	5	-	684.95	995
RF10	335.2	83.8	10	-	648.88	995
RF20	335.2	83.8	20	-	576.66	995
RF30	335.2	83.8	30	-	504.72	995
RC5	335.2	83.8	-	5	721	945
RC10	335.2	83.8	-	10	721	895.5
RC20	335.2	83.8	-	20	721	796.17
RC30	335.2	83.8	-	30	721	696.5
RFC5	335.2	83.8	2.5	2.5	702.77	970
RFC10	335.2	83.8	5	5	684.95	945
RFC20	335.2	83.8	10	10	648.88	895.5
RFC30	335.2	83.8	15	15	612.83	845.72

Normal OPC specimen without any additives or TA was used. Specimen C is the control specimen containing 20% of GGBFS as a replacement from the dry weight of OPC. Specimens RF5, RF10, RF20 and RF30 are the RC that contained fine TAs of 5%, 10%, 15% and 20%, respectively as a partial replacement from the weight. Besides, specimens RC5, RC10, RC15 and RC20 enclosed coarse TAs of same percentage as a partial replacement from the weight. Yet again, specimens RFC5, RFC10, RFC20 and RFC30 were included with both rubber aggregates (fine and coarse clusters) as a replacement in each mixture with equal percentages.

The dry materials such as cement, GGBFS, aggregates were mixed together for 1 minute in the mixer with the proportion designed. Then, 50% of TAs and 50% of water was added to the mix over a period of 30 seconds. Next, the remaining 50% of TAs was gradually added with the residual 50% of water over a period of 60 seconds. All samples were cured in water in a curing room at an ambient temperature of (23 ± 3) °C according to ASTM C192/C192 M-07 standard with 60% of relative humidity (RH) after molded for 1 day. The curing periods (3, 7, 28, and 90 days) were decided depending on the testing method.

4. Results and Discussion

4.1 Slump (ASTM C143)

Slump test was performed to measure the workability of fresh concrete to be applicable for constructional purposes. The workability of the RC was found to enhance and the compressive strength was reduced with the increase in water content. It was asserted that workability of the proposed RC with the designated strength must be considered as a determining factor for construction applications.

Figure 3 displays the workability of RC containing 20% of GGBFS with different percentages of rubber TAs. The slump value of the control specimen with 20% of GGBFS was lower (42 mm) compared to OPC (58 mm). The workability of concrete was enhanced with the increase in TA levels, wherein the slump values were reached to 41, 44, 35, and 27 mm for RF5, RF10, RF20, and RF30 specimens containing 20% of GGBFS, respectively. Besides, the slump values for RC5, RC10, RC20, and RC30 specimens were 40, 41, 37, and 34 mm, respectively. Meanwhile, the corresponding workability of RFC5, RFC10, RFC20, and RFC30 mixes were discerned to be 45, 47, 42, and 32 mm. The workability of the concrete containing GGBFS was decreased with increasing fineness, which was due to more water absorption by finer martial with higher surface area. Besides, the higher workability of concrete for low-volume rubber replacement was attributed to the shape of rubber aggregates that reduced the friction between the components of the concrete mixture. Conversely, the observed lower workability of concrete for high-volume rubber aggregates content was ascribed to the higher specific surface and roughness of the rubber aggregates.

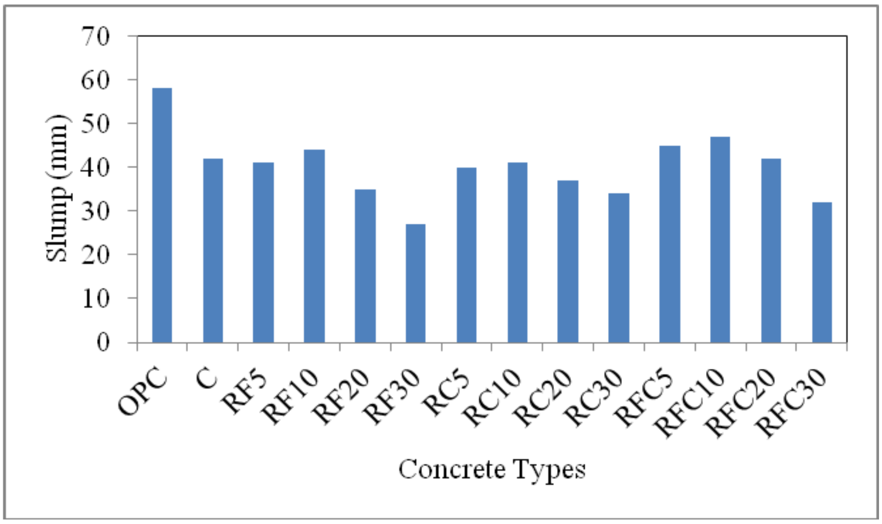

Figure 3. Influence of TAs on the slump of proposed RCs.

4.2 Compacting Factor (BS 1881: Part 103)

Figure 4 shows the results on compacting factor for fresh RCs with their respective slump values. It is worth noting that the test for the compacting factor is more precise compared to slump test particularly for concrete specimens having intermediate and low workability that corresponds to the compacting factors in the range of 0.9 to 0.8. However, this test is unsuitable for concrete mix with compacting factor below 0.7. The compacting factor of the proposed RC was found to diminish with the increase in the rubber aggregate percentages in the concrete mix. OPC specimen revealed the the highest vale of compacting factor (0.924) which is somewhat higher than the one designed with 20% of GGBFS (0.908). All the specimens containing rubber aggregates exhibited a compact factor value within the range of 0.8 to 0.9. The lower compacting factor rubberised concrete can be attributed to the roughness of rubber particles and the higher specific surface area than those of natural aggregates. This reduction may also be related to the poor cohesion between rubber aggregates, cement paste, and natural aggregates.

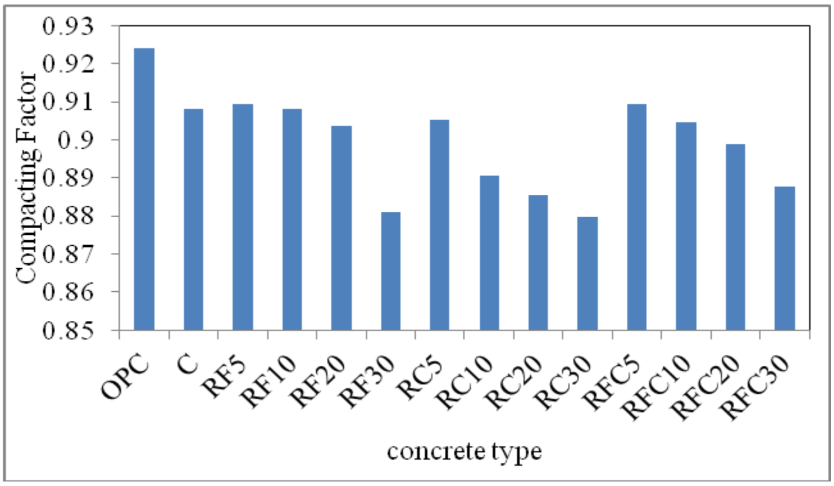

Figure 4. Compacting factor of the studied fresh RCs.

4.3 Compressive Strength

Compressive strength values characterize the quality of the concrete, a measure of resistance of concrete against the axial load. Figure 5 depicts the compressive strength of the proposed RC at varying curing ages (3, 7, 28 and 90 days) obtained in accordance to BS 1881-part 116, 1983 testing procedure. The compressive strength of the prepared RC mixes was found to drop with the rubber aggregates as partial replacement to natural aggregate in the concrete. Moreover, the RC specimen with 20% of GGBFS and 5% of TAs exhibited higher compressive strength than the normal concrete. The observed reduction in the compressive strength of RCs with the increase in the rubber aggregate percentages was attributed to the softer/smoother surface features of rubber lumps than the surrounding rigid/roughened surfaces of cement pastes and natural aggregates. It was argued that such softer and smoother surfaces of rubber clusters could appreciably diminish the linkage (bonding or adhesion) among rubber aggregates and harder cement pastes. However, the mineral composition, hardness and the filler effect of the GGBFS could influence the strength of the RC. These results indicated that the RC modified with GGBFS target can produce higher compressive strength at prolonged curing age.

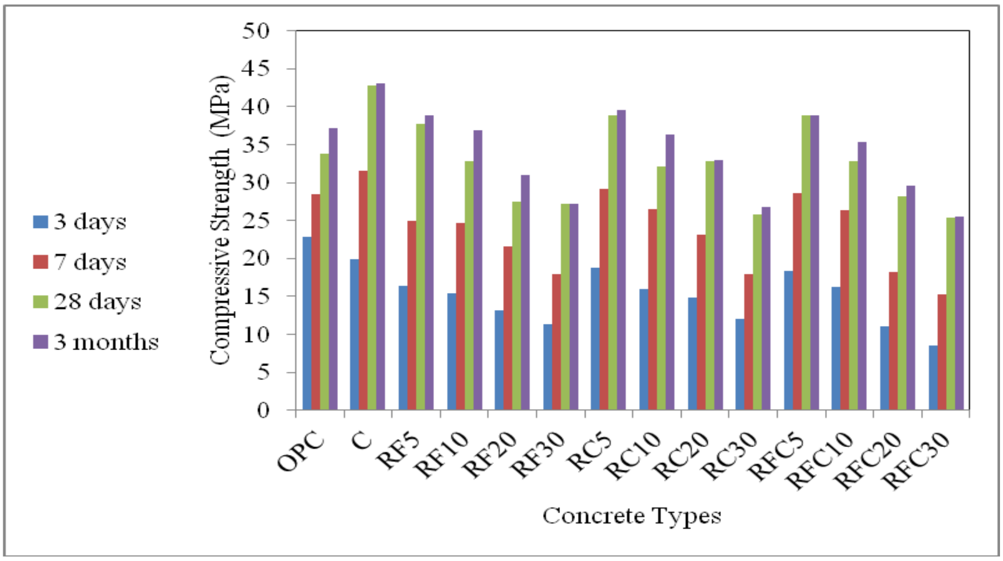

Figure 5. Compressive strength of studied RCs at different curing ages.

4.4 Flexural Strength

Figure 6 presents the flexural strength of concrete containing 5% to 30% rubber aggregates. Following the BS 1881-181:1983 standard, the flexural strength test was performed on 2 prismatic RC specimens of dimension (100 mm × 100 mm × 500 mm) at the curing ages of 7, 28, and 90 days. The measured flexural strength of these 2 samples was taken to calculate the mean value. Irrespective of the curing ages, RC mix containing 5% of TAs manifested higher strength compared to the one comprised of 10%, 20%, and 30% of rubber aggregates. Furthermore, after 90 days of curing the flexural strength of RC specimen with 5% of rubber and 20% GGBFS was higher than OPC. The performance in terms of flexural strength was similar to the compressive strength. Rubber particles owing to high deformability could act as barrier against crack generation and propagation in concrete. Thus, this inclusion of rubber chunks was expected to improve the flexural strength of RC. Moreover, the results were opposite where the weak bonding between TAs and cement paste could worsen the situation and the strength was deteriorated.

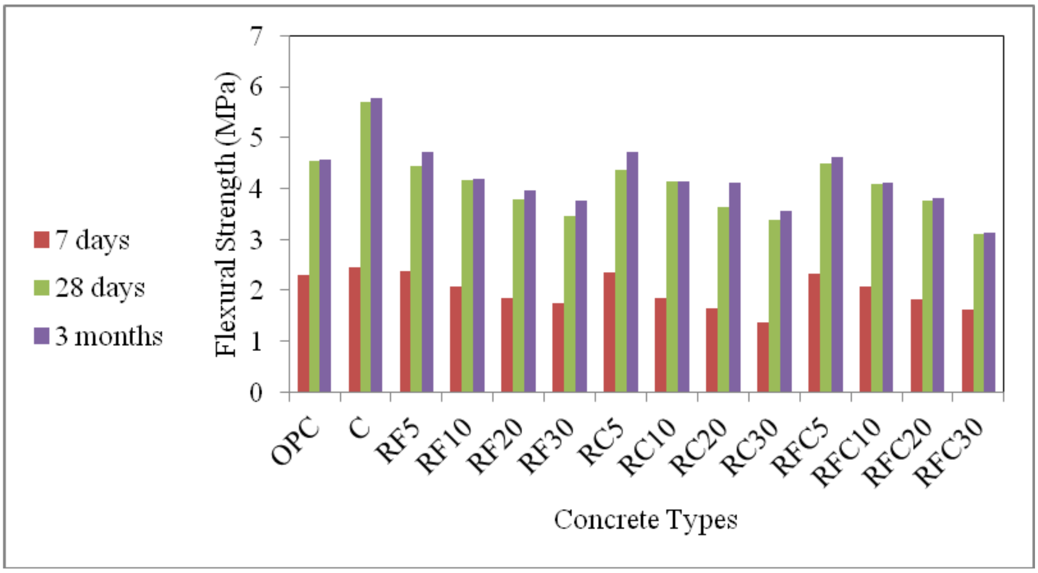

Figure 6. Flexural strength of the proposed RC at different curing ages.

4.5 Indirect Tensile Strength (ASTM C496/C496M-11)

Figure 7 displays the development of splitting tensile strength of RC at varying curing ages. In this method, test specimens in the form of cylinder with dimension (100 mm × 200 mm) (diameter by length) was subjected to a load until the specimen was split into two hemispheres according ASTM C496/C496M-11 standard.

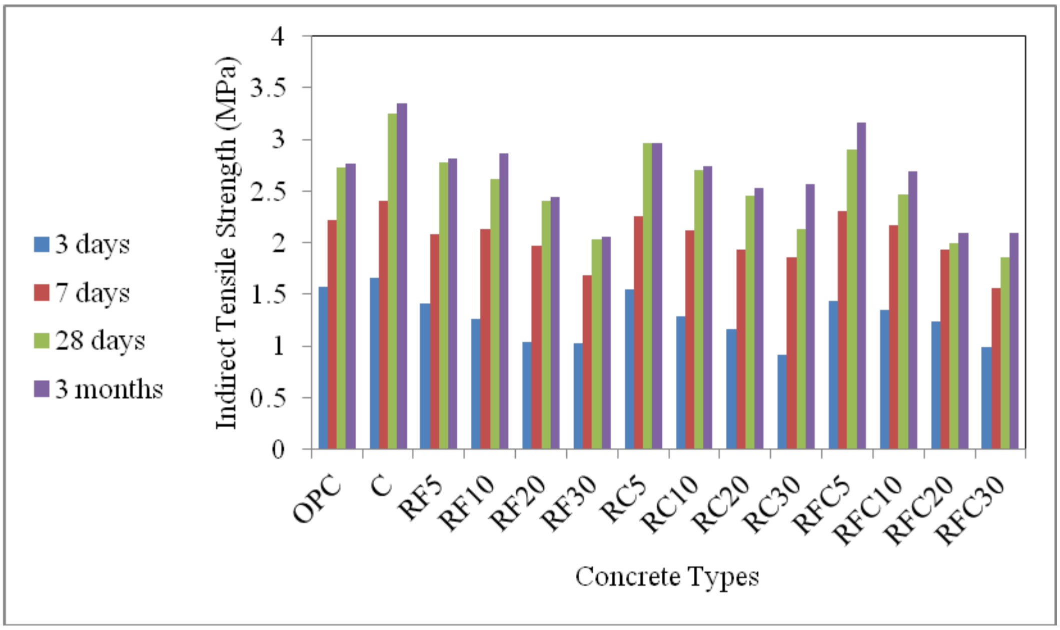

Figure 7. Splitting tensile strength of studied RCs at different curing ages.

The tensile strength of concrete incorporated with rubber aggregates is generally less than that of normal concrete. The tensile strength showed further reductions at higher rubber aggregate content. Moreover, specimens OPC, RF5 and RC10 revealed almost the same splitting tensile strength at 3, 7, 28 and 90 days. The splitting tensile strength at 28 days of curing for the concrete specimen containing 20% of GGBFS without TA inclusion revealed the highest value. However, the RC comprising of TA showed reduced splitting tensile strength. The weak bonding between cement paste and rubber aggregate could be responsible for the failure of concrete in the weak interfacial zone at the beginning. The other factor is the nature and proportion of rubber aggregates as compared to conventional aggregates. The stiffness of rubber particles was very low due to their easy deformability. Therefore, the rubber particles just acted as voids and cavities to cause stress concentration on the periphery of the rubber aggregate. This in turn resulted in a declination in the splitting tensile strength of modified concrete.

4.6 Modulus of Elasticity (C469/C469M – 10)

Figure 8 illustrates the elastic modulus of RC. Higher modulus of elasticity of a material implies the requirement of larger force to stretch the bond, indicating greater binding energy of chemical constituents. Conversely, a lower modulus of elasticity of concrete containing TAs could signify lesser binding energy or weak bonding between rubber lumps and surrounding concrete composites. Vertical strain gauges (type PL-60-11-3L) was used to measure the strain of concrete and one horizontal strain gauge was installed to record the lateral strain.

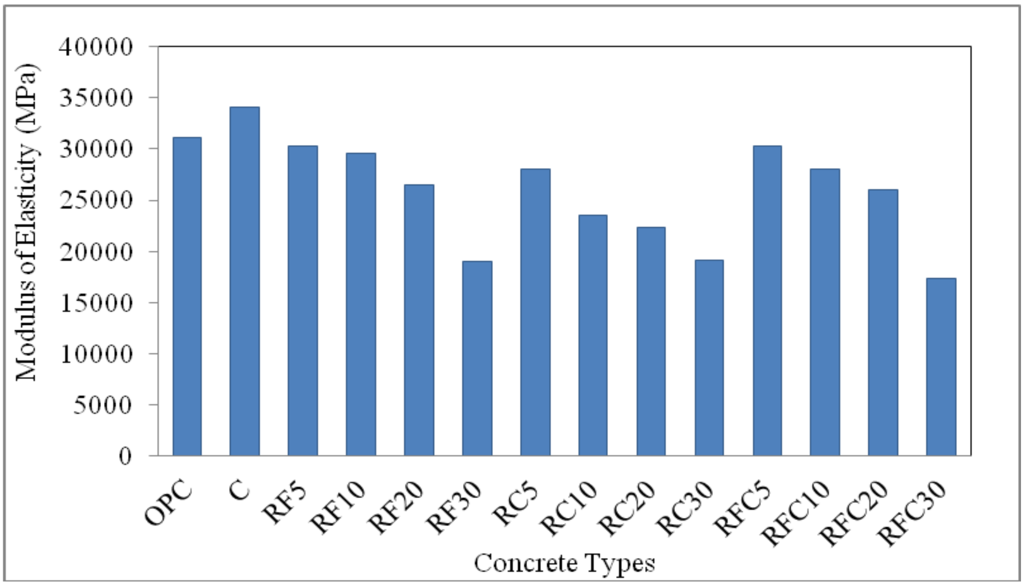

Figure 8. Elastic modulus of proposed RCs.

The modulus of elasticity of concrete specimen containing GGBFS was higher compared to the OPC. However, the modulus of elasticity was reduced with the increase in the TA contents in the RCs. The value of elastic modulus for RFC30 mix was lowest. Meanwhile, RF5 and RFC5 specimens revealed the highest modulus of elasticity. Modulus of elasticity was increased with the increase of compressive strength. Generally, replacement of GGBFS in concrete increases the modulus of elasticity. However, it was found that the inclusion of rubber aggregates in concrete could reduce the elastic modulus considerably.

5. Conclusions

Based on the abovementioned test results the following conclusions were drawn:

- The workability of RC was reduced due to the inclusion of GGBFS, which was ascribed to the fineness of its piratical and absorption capacity.
- Slump and compacting factor of the proposed RC were reduced with the increase in the rubber fraction in the concrete mix.
- Amongst all the RC, the MRC5 specimen revealed the highest slump value. The slump values for MRF5, MRC20, MRFC5, and MRFC10 specimens were above 50 mm. However, slump vale for MRF30 and MRFC30 specimens were below 40 mm.
- Concrete mixes containing GGBFS attained the highest compressive strength.
- Compressive strength of concrete mix with 5% of TAs was higher compared to OPC.
- Flexural strength of RC containing 20% of GGBFS at 90 days of curing was strongly affected.
- Modified concrete with GGBFS mixes exhibited higher tensile strength than the one included with TAs.
- In short, incorporation of RAs (fine and coarse grain) into the concrete as partial replacement to GGBFS was discerned to diminish the modulus of elasticity In fact, concrete containing coarse aggregates displayed the lowest elastic modulus compared to those without rubber aggregate inclusion.

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