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DURABILITY OF GREEN CONCRETE WITH TERNARY CEMENTITIOUS SYSTEM CONTAINING RECYCLED AGGREGATE CONCRETE AND TIRE RUBBER WASTES

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Abstract

All over the world billions of tires are being discarded and buried representing a serious ecological threat. Up to now a small part is recycled and millions of tires are just stockpiled, landfilled or buried. This paper presents results about the properties and the durability of green concrete contains recycled concrete as a coarse aggregate with partial replacement of sand by tire rubber wastes for pavement use. Ternary cementious system, Silica fume, Fly ash and Cement Kiln Dust are used as partial replacement of cement by weight. Each one replaced 10% of cement weight to give a total replacement of 30%. The durability performance was assessed by means of water absorption, chloride ion permeability at 28 and 90 days, and resistance to sulphuric acid attack at 1, 7, 14 and 28 days. Also to the compression behaviors for the tested specimens at 7, 14, 28 and 90 days were detected. The results show the existence of ternary cementitious system, silica fly ash and Cement Kiln Dust minimizes the strength loss associated to the use of rubber waste. In this way, up to 10% rubber content and 30% ternary cementious system an adequate strength class value (30 MPa), as required for a wide range of common structural uses, can be reached both through natural aggregate concrete and recycled aggregate concrete. Results also show that, it is possible to use rubber waste up to 15% and still maintain a high resistance to acid attack. The mixes with 10%silica fume, 10% fly ash and 10% Cement Kiln Dust show a higher resistance to sulphuric acid attack than the reference mix independently of the rubber waste content. The mixes with rubber waste and ternary cementious system was a lower resistance to sulphuric acid attack than the reference mix.

Keywords: Rubber wastes, Recycled concrete, Silica fume, Fly ash, Cement Kiln Dust (CKD), Water absorption, Sulphuric acid attack, Chloride ion, Permeability, Durability.

Abbreviations	
CKD	Cement Kiln Dust
Fly Ash	FA
FRA	Fine Recycled concrete aggregates
KSA	King Saudi Arabia
NA	National Aggregates
NCA	Natural Coarse Aggregates
NMS	Nominal Maximum Size
PC–SL–FA	Portland cement, granulated blast-furnace slag and fly ash system
RA	Recycled Aggregates
RCA	Recycled Concrete Coarse aggregates
SF	Silica Fume

1. Introduction

Using waste tire rubber as an aggregate for pavement construction development is an effective approach to utilize waste tire. Huge quantities of waste tires all over the world are being discarded and buried causing serious environmental pollution. In the future (after twenty years) the number of tires from motor vehicles is expected to be increased very rapidly, small part of these tires to be discarded in a regular basis. Over 50% of waste tires are discarded without any treatment. Disposal of waste tires has been a major environmental issue in cities all around the world. The easiest and cheapest method of tire disposal is to burn them. But the pollution it creates makes the method unacceptable and is banned by law in many countries. It has been estimated that around one billion tires are withdrawn from use in the world every year at the present time [1-3].

A possible solution for this problem is the use of tire rubber waste as aggregate replacement in concrete. Two different techniques are used to obtain the rubber aggregate from the waste tires. The first technique is the mechanical grinding at ambient temperature, while the second technique is the cryogenic grinding at a temperature below the glass transition temperature. The first method generates chipped rubber to replace coarse aggregates. As for the second method it usually produces crumb rubber to replace fine aggregates. Some researchers conducted on the use of waste tire as aggregate replacement in concrete are showing that rubber aggregates reduce concrete workability and compressive strength [4, 5]. The strength loss is much more profound when coarse rubber aggregates are used which is due to the low adhesion between these wastes and the cement paste, but several authors recommended different treatments to enhance the adhesion of the rubber aggregates [6–8]. Previous investigations also show that concrete composites containing tire rubber waste are known for their high toughness, meaning that they are specially recommended for concrete structures located in areas of severe earthquake risk and also for the production of railway sleepers [9-12].

In recent years the generation of waste by-products materials with pozzolanic properties was increasing rapidly, and consequently create serious environmental problems, which detect the need to increase the efforts for greater utilization in different market sectors. It was mentioned that the construction sector clearly absorbs the majority of such materials, by incorporating them in hydraulic binders as supplementary cementing materials [13]. For a variety of reasons, the concrete construction industry is not sustainable. First, it consumes huge quantities of virgin materials. Second, the principal binder in concrete is Portland cement, the production of which is a major contributor to greenhouse gas emissions that are implicated in global warming and climate change. Third, many concrete structures suffer from lack of durability, which has an adverse effect on the resource productivity of the industry. An experimental program explained that the high-volume fly ash concrete system addresses all three sustainability issues, and its adoption will enable the concrete industry to become more sustainable [14].

Many researches proved success of using ternary blended cements to enhance the performance of concrete compared with binary blended cements or regular Portland cement. Ternary blended cement consisting of Portland cement, granulated blast-furnace slag and fly ash (PC–SL–FA system) was developed in Japan for mass concrete construction due to its very low heat of hydration [15]. This system can be treated as slag cement incorporating fly ash. The addition of fly ash can increase workability and reduce bleeding of slag cement concrete. But in the same time it was found that strength development of this system is relatively slower at early age. Incorporated silica fume in slag cement or fly ash cement, the ternary PC–SL–SF (Portland cement, blast-furnace slag and silica fume) and PC–FA–SF (Portland cement, fly ash and silica fume) blended cements developed and commercially manufactured in Canada. More details about the properties of concrete containing Portland cement, fly ash and silica fume as blended cements are mentioned in studies carried out by [16-18].

The reuse of structural concrete elements to produce new concrete aggregates is accepted as an alternative to dumping them and is favourable to the sustainability of natural reserves [19]. The use of recycled aggregates (RA) is an important step forward in the development of a more sustainable society. More recent researches on concrete made with coarse recycled concrete aggregates and fine recycled concrete aggregates (FRA) have led to positive results concerning the use of RA in structural concrete [20-24].

The studies about the properties of recycled aggregate concrete with tire rubber wastes are abundant the ones related to the durability and are scarce justifying further investigations. Besides, so far investigations using rubber wastes were made using normal-strength concretes thus meaning that using a low water/binder concrete constitutes a research area yet to be explored.

2. Experimental Work

2.1. Materials

In the current experimental work the following materials are used:

Cement: ASTM Type I ordinary Portland cement locally produced with 28 days compressive strength 60 MPa was used for all the concrete mixtures.

Mineral admixtures: Mineral admixtures used in this investigation including silica fume (SF), fly ash (FA), and cement kiln dust (CKD). The SF used was a dry un-compacted powder with SiO_2 content of 93%. The amount retained on a 45-lm sieve was 1.6%. Fly ash procured from Egypt power plants and can be classified as Class C according to ASTM C 618. The CKD were provided by cement factory in

King Saudi Arabia (KSA). CKD is defined as a fine-grained, solid, highly alkaline by-product waste material, the particles diameter range between few lm and 50 lm that removed from cement kiln exhaust gas by air pollution control devices. CKD forms in cement plants during the manufacturing process when the kiln's temperature is ranging between 800 and 1000^{o}C. The concentration of its constituents is varying based on the initial fed raw materials; however, it generally contains relatively high percentage of alkalis such as K_2O and Na_2O. It was experimentally found that, in KSA cement plants, the variation of these compositions is not significant due to the similarity in the raw materials (quarries). Typically, CKD is different from plant to another, based on the fed materials, and it generally disposes in land-based disposal units i.e. landfills, waste piles, etc. and it is not returned to the production process. The chemical composition and physical properties of the cement, SF, FA, and CKD are given in Table 1

Table 1.Chemical compositions of OPC, BFSC, and CKD.

Material	OPC	SF	FA	CKD
SiO_2 (%)	21.47	93	25.83	12.03
AL_2O_3 (%)	3.21	1.0	5.25	1.12
Fe_2O_3 (%)	5.22	0.5	7.71	2.45
CaO (%)	62.7	0.91	57.4	49.8
MgO (%)	2.32	0.27	2.73	1.84
SO_3 (%)	2.36	-	3.1	6.35
NaO_3 (%)	2.40	-	2.13	3.87
K_2O (%)	0.41	-	0.29	2.66
Ignition loss (%)	1.23	2.0	1.12	18.2

Rubber: Rubber aggregates used in this study were obtained by shredding worn tires. The rubber has an average particle diameter of 1-3.5mm sieve size, a specific gravity of 1.05, and a melting temperature of 170^{o}C. The rubber used at different levels 5%, 10% and 15% as a partial replacement of sand.

Fine aggregate: Fine aggregate is fine clean sand with 2.58 specific gravity and 2.91 fineness modulus and water absorption rate of 0.65%. The fine aggregate was confirmed the ASTM requirements (ASTM C-33).

Natural coarse aggregates (NCA): NCA obtained from Crushed stones with a specific gravity of 2685kg/m^3 and water absorption rate of 0.83%, was used. The size of NCA had 5-14 mm size continuous grading.

Recycled concrete: Recycled concrete coarse aggregates (RCA) sourced from a recycling facility in KSA, was used. According to the quality control requirements of the recycling facility, the recycled aggregate contained less than 0.5% by weight of wood and particles less dense than water and less than 1% by weight of other foreign materials. Therefore, the recycled aggregate used in this study could be considered as recycled concrete aggregate. The nominal sizes of the natural and recycled coarse aggregates were 14 mm and their particle size distributions conformed to the requirements of ASTM C-33. The porosity of the aggregates was determined using mercury intrusion porosimetry. The specific gravity and water absorption rate of the RCA were 2510 kg/m3 and 4.7%, respectively, and the RCA had continuous grading 5-14 mm size. The physical and mechanical properties of the coarse aggregate are summarized in Table 2.The current experimental work materials **(**a-Natural aggregate, b-Recycled aggregate, c-Rubber) are explained in Fig. 1.

Table 2. Properties of natural and recycled aggregates.

Type of aggregate	Specific gravity	N.M.S	Water ab-sorption %	Porosity %	L.A abrasion
Natural	2.69	14	1.0	1.58	3.8-6.2
Recycled	2.51	14	4.7	8.1	11-14.7

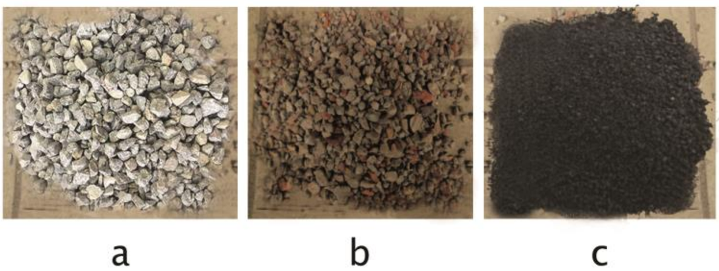


Fig. 1. The current experimental work materials.
(a-Natural aggregate, b-Recycled aggregate, c-Rubber).

Super plasticizer: A second generation super plasticizer, based on poly-carboxylic either polymers, was used at appropriate percentages in order to retain the slump of the fresh concrete between 120 and 180 mm.

2.2. Mix design and proportions.

The concrete mix was designed according to ACI method 211, to have 28 days cylinder compressive strength of 60 MPa. Concrete mixes with a 450 kg/m^3 of binder was designed. The maximum aggregate size was 14 mm and the free water binder ratio was 0.35. The concrete specimens were conditioned at a temperature equal to 21 ± 2 0C cured in tap water plastic tanks until they have reached the testing ages. The concrete mixtures were named according to their content. For instance is related to a concrete mixture with 5%, 10% and 15% of rubber waste, 10% silica fume, 10% fly ash and 10% of Cement Kiln Dust (CKD). This mixture had an average 28 days compressive strength of 62 MPa. The concrete mixes for natural aggregate and recycled aggregate are described in Table 3.

Table 3. Mix design and proportions.

Mix. No.	Cement (kg)	Mineral Admixture (kg)			Sand (kg)	Rubber (kg)	C. Agg (kg).	Water (L)	SP (L)
		S.F	F.A	CKD					

Natural coarse aggregate concrete mix									
0%R,0%M	450	0	0	0	1233	0	1256	157.5	9.5
0%R,30%M	315	45	45	45	1233	0	1256	157.7	9.5
5%R,30%M	315	45	45	45	1168	65	1256	157.5	9.5
10%R,30%M	315	45	45	45	1103	130	1256	157.5	9.5
15%R,30%M	315	45	45	45	1038	195	1256	157.7	9.5
Recycled coarse aggregate concrete mix									
0%R,0%M	450	0	0	0	1233	0	1167	157.5	9.5
0%R,30%M	315	45	45	45	1233	0	1167	157.7	9.5
5%R,30%M	315	45	45	45	1168	65	1167	157.5	9.5
10%R,30%M	315	45	45	45	1103	130	1167	157.5	9.5
15%R,30%M	315	45	45	45	1038	195	1167	157.7	9.5

%R: Rubber content, %M: Mineral Admixture contents (10%SF, 10%FA and 10% CKD).

2.3. Specimens preparation

The concrete mixes were prepared using a tilting drum mixer of 0.1 m^3 capacity. The interior of the drum was initially washed with water to prevent water absorption. The coarse and medium aggregate fractions were mixed first, followed by adding the amount of water absorbed by the aggregates and allowed to rest for 30 min to minimize the variation in the initial slump caused by the high water absorption of recycled aggregates; then sand was added, followed by adding binder materials (cement, SF, FA, and CKD), and the water containing about 75% of the super plasticizer. One-fourth of the super plasticizer was always retained to be added during the last 3 min of mixing period. The concrete mixes were poured in cylindrical molds, and compacted using a vibration table at low speed. After each mold was properly filled the vibration speed was increased to medium speed to ensure sufficient compaction.

After casting, the specimens were covered with wet burlap and stored in the laboratory at 23 0C and 65% relative humidity for 24 h and then demoulded and placed under water. Each specimen was labeled as to the date of casting, mix used and serial number. The specimens were then taken out of water a day before testing and dried in air.

2.4. Tests

2.4.1. Compressive strength

Tests were performed on cylinder of 150mm diameter and 300mm height concrete specimens. The average concrete compressive strength was 62 MPa. Compressive strength for each mixture was obtained from an average of three cylinder specimens determined at the age of 7, 14, 28 and 90 days of curing. Fig.2 explain test set –up.

Fig.2 Test set –up,

2.4.2. Water absorption

As per ASTM C 642 [25], water absorption was determined using 100×100×100 mm cube specimens for each concrete mixture at each testing age. The water absorption (WA%) of each concrete was calculated through Eq. (1) where W_1 and $W_2$are oven dry and saturated surface dry weights, respectively. Three specimens from each mixture were tested at the ages of 28 and 90 days and the average values were reported.

$$WA\% = \left(\frac{W_2 - W_1}{W_1}\right) x100 \quad (1)$$

2.4.3. Chloride ion permeability

The rapid chloride ion permeability test was conducted in accordance to ASTM C-1202 [26]. Three specimens of 100 mm in diameter and 50 mm in thickness conditioned according to the standards were subjected to 60-V potential for 6 h. The total charge passed through the concrete specimens was determined and used to evaluate the chloride ion permeability of each concrete mixture.

2.4.4. Resistance to sulphuric acid attack

The resistance to acid attack followed a variation of the ASTM C-267 (Standard test methods for chemical resistance of mortars, grouts, and monolithic surfacing and polymer concretes). The test used in the present investigation consists in the immersion of 150x300mm concrete specimens in a 10% of sulphuric solution during 28 days. The resistance to acid attack was assessed by the differences in weight of dry specimens before and after acid attack at 1, 3, 7, 14, 28 and 90 days.

3. Results and Discussion

3.1. Compressive strength

The compressive strength development as a function of time for the natural aggregate and recycled aggregate concretes of different rubber tire contents and ternary cementious system is illustrated in Fig. 3. The standard deviation was low and the coefficient of variation do not exceed 10% meaning that the results were statistical relevant. Similar behavior was observed for all mixes. The increase of rubber wastes leads to serious compressive strength loss as shown in Fig.3. Thus, a tire–rubber concrete specimen loses its strength depending on its tire content. After 14 days, the compressive strength development of the RAC with and without mineral addition was slowed down with respect to the NAC concrete. The mix made from NA and with 5% rubber wastes and 30% ternary cementitious system (5%R and 30%M) and the mix made from RA and with 5% rubber wastes and 30% ternary cementitious system (5%R, 30%M) are the only mixes that is associated to a high compressive strength, above 51 MPa, respectively and 40 MPa exceeding the majority of compressive strength classes used in the construction industry.

When compared to the compressive strength of the reference mix, the mix of 5%R and 30%M has a 37.5% compressive strength decrease at 28 days curing. The mixes with a higher rubber percentage show a very severe compressive strength loss. This reduction due to a low modulus of elasticity of rubber wastes with respect to normal aggregates, rubber aggregates act as large pores, and do not significantly contribute to the resistance to externally applied loads. Thus, a tire–rubber concrete specimen loses its strength depending on its tire content [28].

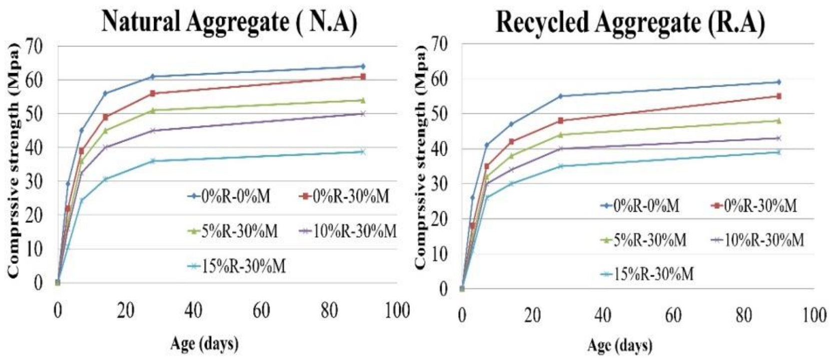
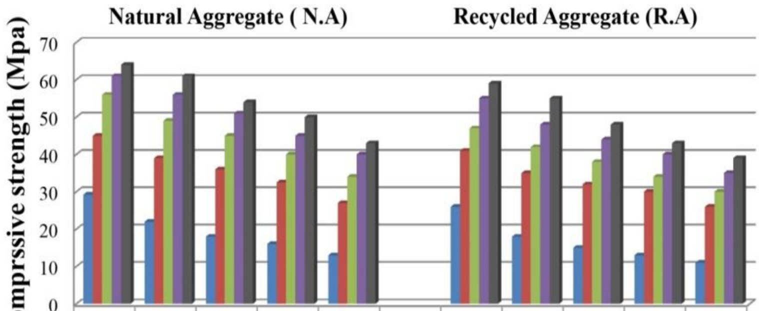


Fig. 3.Compression behavior of the mixes with different levels of rubber for natural aggregate and recycled aggregate mixes.

The values of compressive strength of mixes with partial replacement of cement by ternary cementitious system (SF, FA, and CKD) for various levels of rubber content are presented in Fig. 4. The results showing that the replacement of cement by 30 % ternary cementious system (SF, FA, and CKD) reduced the compressive strength by about 15% at 28 days and this reduction decrease at 90 days to reach 5-7% for natural aggregates (NA) mixes and RA mixes. Figure 4 shows also the compressive strength of mixes with rubber wastes and partial replacement of cement by ternary cementitious system. In this way, up to 10% rubber content and 30% ternary cementious an adequate strength class value (30 MPa), as required for a wide range of common structural uses, can be reached both through NA concrete and RA concrete, by suitably decreasing water/cement with the aid of a superplasticizing admixture in order to maintain the same workability. The results show the synergetic effect of ternary cementitious and recycled aggregate minimizes the strength loss associated to the use of rubber waste.

Since the porosity of the recycled aggregates is higher than that of the normal aggregates, the reason for this strength reduction probably is due to the presence of a weaker aggregate. Therefore, the use of recycled aggregates has more influence on the compressive strength as the cement matrix gets stronger, this being the strength controlling link of the composite system. This effect is not evident in the case of silica fume addition and it is not even noticeable in the presence of fly ash because of its pozzolanic activity. The effectiveness of silica fume addition at early curing times is particularly evident, due to its densifying effect in addition to the pozzolanic activity [27]. Moreover, this result attributed to that fly ash and CKD in ternary cementitious system has slow hydration characteristics thus providing little contribution to early age strength, as to SF possess a high reactivity with calcium hydroxide having the ability to accelerate cement hydration. The reduction in strength could also attributed to the significant increase in free lime content in CKD that increases the amount of Ca(OH)2 due to the its reaction with water. Calcium Hydroxide has a volume larger than water; therefore, this volume increase generates internal stresses that weaken the hardened matrix



	0%R-0%M	0%R-30%M	5%R-30%M	10%R-305M	15%R-30%M		0%R-0%M	0%R-30%M	5%R-30%M	10%R-305M	15%R-30%M
3-DAYS	29.25	22	18	16	13		26	18	15	13	11
7-DAYS	45	39	36	32.5	27		41	35	32	30	26
14-DAYS	56	49	45	40	34		47	42	38	34	30
28-DAYS	61	56	51	45	40		55	48	44	40	35
90-DAYS	64	61	54	50	43		59	55	48	43	39

Fig. 4. Compressive strength of the mixes with partial replacement of cement by Silica fume, fly ash and Cement Kiln Dust (CKD); and rubber wastes for natural aggregate and recycled aggregate.

3.2. Mode of failure

By visual inspection of concrete specimen behavior the failure duration, defined as the duration to concrete failure, for NA concrete is abrupt and explosive. In contrast, the tire–rubber concrete failure duration is more gradual, since the concrete becomes more flexible with increasing tire particle substitution of normal aggregates. Figures 5(a) and (b) demonstrate that the failure parameters grow uniformly from the bottom to the top of a natural and recycled aggregate of specimen with rubber wastes. Also as shown in Figs. 5(a) and (b) considerable lateral deformations are observable in tire–rubber concrete specimens after an entire loading process. Tire–rubber concretes are able to withstand loads beyond the peak load, which is referred to as post-failure strength. Failure states in concrete specimens, as shown in Fig. 5(a), are accompanied with the separation of pieces or slices from the specimen. For concrete containing tire particles, the failure state was not accompanied by any detachment due to the bridging of cracks by rubber particles.

Tire–rubber concrete specimens did not exhibit any detachment, despite losing a considerable amount of strength as shown by the 5%R and 30%M specimens, refer to Fig.5(a). Also it was observed from Fig. 5(b) that the failure happened through the recycled aggregates (the recycled aggregates being the weakest point) producing two similar symmetric faces. It typically did not happen in the interfacial transition zone. In fact, for low water/cement the old cement paste of RAC had a lower strength than the cement paste of the concrete Mixture REC, i.e. the quality of the new paste was superior to the old paste. Consequently, RAC represents the weakest component and the strength controlling link of the composite system [29]

The failure mechanism of tire rubber specimens can be discuss as that the tire–rubber concrete specimens present large deformations compared to plain concrete specimens. During the unloading process, the flexible behavior of tire particles decreases the internal friction among the concrete elements, and recovers extra strain. Failure properties, like discontinuities and cracks, propagated uniformly and gradually in tire–rubber concrete specimens. In contrast, the propagation of failure symptoms was abrupt and concentrated for plain concrete.

The lateral deformations of tire–rubber concrete specimens are larger than those of plain concrete specimens; however, because of the porosity due to the substitution of tire particles, Poisson's ratios for tire–rubber concrete are slightly more than those for plain concrete. It is important to note that the behavior of rubberized concrete is not perfectly elastic; therefore Poisson's ratio is not constant for the entire loading process. Poisson's ratio increases and approaches 0.5 as the behavior of rubberized concrete become plastic-like.

3.3. Water absorption

Water absorption of the mixes tested as per ASTM C 642 [26] is depicted in shown in Fig. 6. It was observed that the water absorption of the concretes varied from 2.8% to 3.8% and from 2.6% to 3.6% at 28 and 90 days depending on the crumb rubber and ternary cementious system, for NA mixes respectively. While it was observed that the water absorption of the concretes varied from 3.08% to 4.18% and from 2.86% to 3.96% at 28 and 90 days depending on the crumb rubber and ternary cementious system, for RA mixes respectively. As expected the highest water absorption was measured for the mixture having 15% rubber. However, incorporating ternary cementious system appeared to be effective in the reduction of water absorption such that the effect being more pronounced. For example, the mixture (containing 0% rubber and 0% ternary cementious system) had a water absorption value of 2.5% at 90 days while that of the mixture (containing 0% rubber, 30% ternary cementious system) was 2.9% indicating about 16% reduction.

The beneficial effect of ternary cementious system in reducing the water absorption was noticeable due to the filling effect of it at early ages and its pozzolanic reaction at later ages. In the presence of ternary cementious system, the filling effect is immediate, and the pozzolanic reaction is considerably high within 90 days. Using of rubber wastes made the concretes more absorbent with an increasing rate with the rubber content. This result attributed to the increase in porosity with the rubber phase in the mixtures and probably due to some deviations of rubber particles from sand grain size distribution and/or a slightly higher air amount trapped during mixing procedure of the rubberized concretes.

3.4. Chloride ion permeability

The chloride ion permeability test results as a function of crumb rubber and ternary cementious system as well as testing age are depicted in Fig. 7. The data presented in Fig. 5 indicated that the chloride ion permeability were in the range of 2161C to 2792 C and 1888C to 1220C at 28 and 90 days, respectively for natural aggregate mixes. The chloride ion permeability were in the range of 2376C to 3069 C and 2097 C to 1345 C at 28 and 90 days, respectively for recycled aggregate mixes. Using ternary cementious system only has strong positive effect to reduce the chloride ion penetration especially at 90 days.

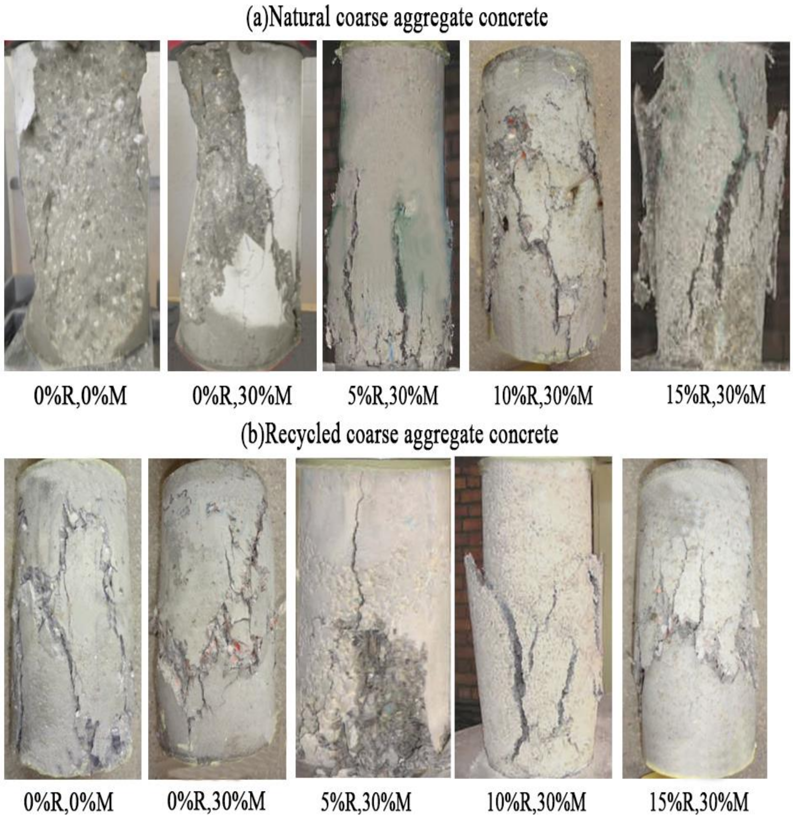
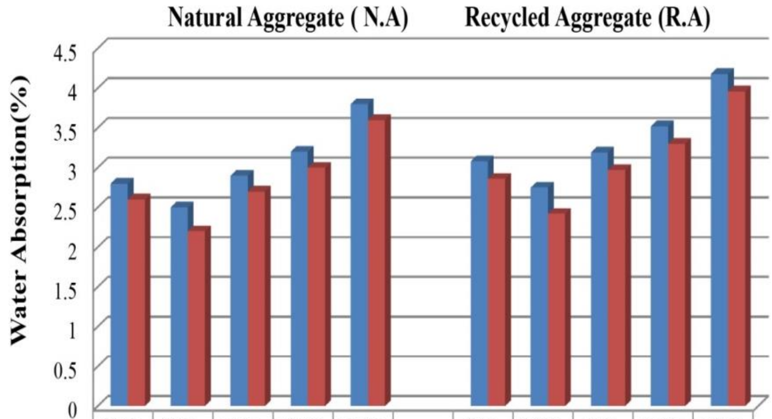


Fig. 5. Mode of failure (a) natural coarse aggregate, (b) recycled coarse aggregate, mixes with and without ternary system and rubber wastes.



	0%R-0%M	0%R-30%M	5%R-30%M	10%R-305M	15%R-30%M		0%R-0%M	0%R-30%M	5%R-30%M	10%R-305M	15%R-30%M
28- DAYS	2.8	2.5	2.9	3.2	3.8		3.08	2.75	3.19	3.52	4.18
90-DAYS	2.6	2.2	2.7	3	3.6		2.86	2.42	2.97	3.3	3.96

Fig. 6. Water absorption coefficient of mixtures with partial replacement of cement by Silica fume, fly ash and Cement Kiln Dust (CKD); and rubber wastes for natural aggregate and recycled aggregate.

There was a progressive increase in the chloride ion penetration with the increasing the rubber content, As the crumb rubber content increased from 0% to 15% as a replacement of fine aggregate, the chloride ion penetration of increased from 1619 to 2792 C and from 655 to 1220 C at the 28 and 90 days, for natural aggregate mixes respectively. Moreover, an average reduction more than 50% was observed with the extension of the period from 28 to 90 days so that all of the concretes seemed to have low or even very low rating, irrespective of testing age.

As seen in Fig.7, Indeed, when the mixes had included ternary cementious system at 30% replacement level, a chloride ion permeability of 2161C coulomb for the control concrete decreased to 1619C and from 1888C to 655C, at 28 and 90 days respectively. However, when the period was prolonged to 90 days, incorporating the ternary cementious system into the NA and RA rubberized concrete mixtures significantly enhanced the resistance of the concretes against the chloride ion ingress, it was decreased by about 65% NA and RA concrete without rubber wastes. Irrespective of the rubber content, all mixes with 5-15% rubber exhibited an increase by about 80% in the chloride ion permeability for mix 15% R, 30%M compared to mix 0% R, 30%M , thus using ternary cementious system shifted the rating of the concretes from moderate to low or very low at 90 days. This indicated that the negative effect of rubber on the chloride ion permeability remarkably diminished with the use of ternary cementious system at 90 days. This finding is attributed to the long-term reaction of ternary cementious system which refines the pore structure of concrete to reduce the ingress of chloride ions. As a result of the refined pore structure, chloride ion permeability is reduced.

From Figs. 6 and 7, the relationship between the chloride ion permeability and water absorption of the concretes can be noticed for 28 and 90 days. It was observed that chloride ion permeability of the concretes was significantly influenced by the amount of water absorbed.

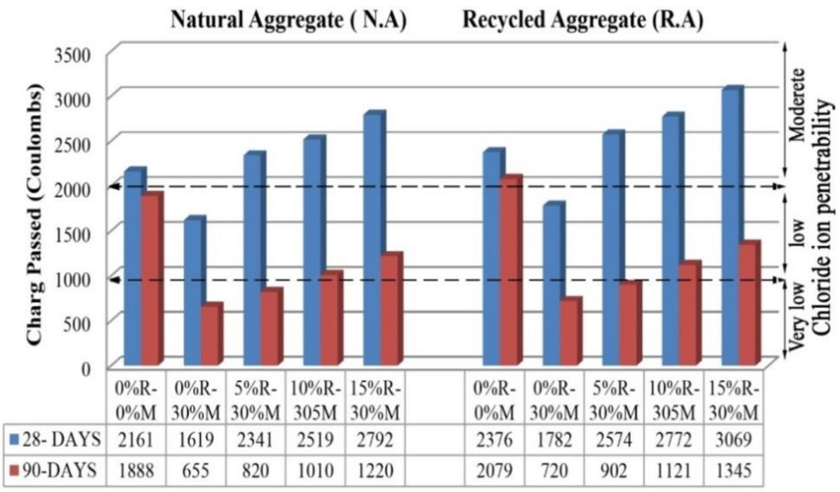


Fig.7.chloride ion permeability of mixtures with partial replacement of cement by Silica fume, fly ash and Cement Kiln Dust (CKD); and rubber wastes for natural aggregate and recycled aggregate.

3.5. Resistance to sulphuric acid attack

The mass loss of mixes after immersion in sulphuric acid solution during 1, 3, 7, 14 and 28 days with and without rubber wastes were represented in Fig. 8. The increase in the rubber percentage leads to a higher mass loss degree. The mix with ternary cementious system underperformed against the reference mix up to 14 days for NA and RA concretes without rubber wastes, after that, the same mass loss or less were recorded compared to o%R,0%M mixes.

These results confirm previous findings about the fact that the presence of pozzolanic admixtures was found to lower the detrimental effect of acid attack on concrete at early ages and was enhanced after that [30]. The mixes with rubber waste and ternary cementious system was a lower resistance to sulphuric acid attack than the reference mix (Fig. 8). The mix with 5% rubber waste and a partial replacement of cement by 30% ternary cementious system has almost lower resistance to sulphuric acid attack of the reference mix (Figs. 8 and 9). The mixes with ternary cementious system without rubber show a higher resistance to sulphuric acid attack than the reference mix at 90 days independently of the rubber waste content. Since the reference mix has higher water absorption than the mixes with ternary cementious system this means that the rate of acid ingress into concrete has a higher influence than the solubility of calcium hydroxide that must be higher in the latter case.

The mix complying with the requirements for concrete structures exposed to highly aggressive chemical environment showed a worst resistance to sulphuric acid attack than the mixes containing rubber wastes and with 30% ternary cementious system. This means that the new mixes with rubber wastes, and 30% ternary cementious system could be recommended for sulphuric acid resistance applications such as sewer pipes concrete, a hot area due to the rapid deterioration of concrete in sewage systems [31]. This also means that the requirements of for concrete structures exposed to highly aggressive chemical environment should be revised.

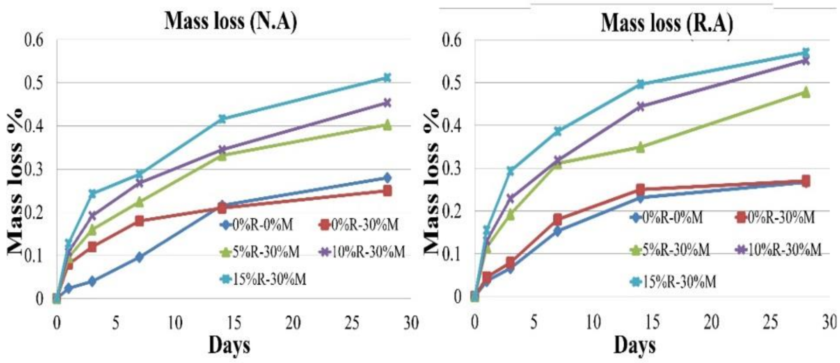


Fig. 8.Mass loss after sulphuric acid attack of mixes with partial replacement of cement by Silica fume, fly ash and Cement Kiln Dust (CKD); and rubber wastes for natural aggregate and recycled aggregate

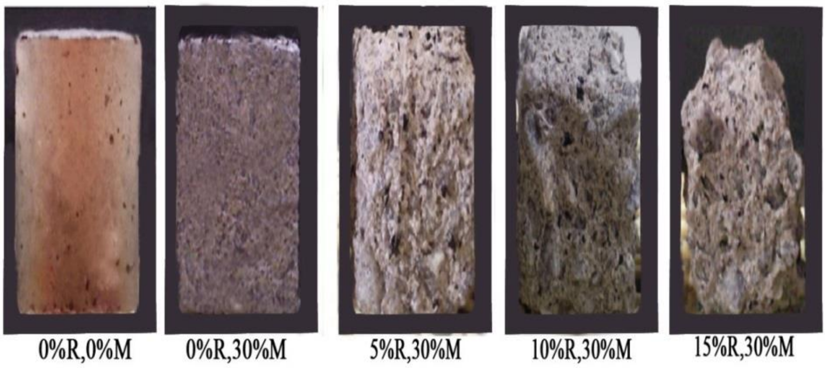


Fig. 9.Photos of concrete specimens with 5% rubber wastes and partial replacement of cement by ternary cementious system after immersion in sulphuric acid solution during 1, 3, 7, 14 and 28 days.

4. Conclusions

From the information presented in this paper, the following conclusions can be drawn:

- The substitution of fine aggregates with tire–rubber particles in concrete results in large reductions in ultimate compressive strength of NA and RA concretes by more than 40% in general. It is possible to use of rubber waste up to 15% and still maintain low water absorption for NA and RA concretes.

- However the synergetic effect between 30%ternary cementious systems minimizes the strength loss by about 50% associated to the use of rubber waste. With the addition of 30% ternary cementious system, the negative effect of crumb rubber on all properties eliminated slightly.
- More ductile behavior is observed for rubberized concrete compared to plain concrete specimens under compression testing. Unlike normal concrete, the failure state in rubberized concrete does not occur quickly and does not cause any detachment in the specimen's elements. Crack width in rubberized concrete is smaller than that of plain concrete, and the propagation of failure symptoms is more gradual and uniform. The failure state in tire–rubber concrete compared to plain concrete is characterized by more deformation.
- Since the presence of the crumb rubber in the concrete, porosity is poorly affected. Therefore, water absorption values of the rubberized concretes increased. Furthermore, increasing the rubber content increased the water absorption. A progressive increase was observed in the chloride ion penetration of the all mixes with the increase in rubber content without ternary cementious system at both of 28 and 90 days test results. Addition of 30% ternary cementious system gives a considerable affect the chloride ion permeability of the all concretes at the 28 days. However, when the period was extended to the 90 days, the long-term reaction of 30% ternary cementious system refines the pore structure of concrete so that ingress of chloride ions decreased drastically.
- The mixes with 30% ternary cementious system show a higher resistance to sulphuric acid attack than the reference mix independently of the rubber waste content. The mix with 5% rubber waste and a partial replacement of cement by 30% ternary cementious system (10%SF, 10%FA and 10%CKD) has considerable resistance to sulphuric acid attack compared with the reference mix.

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