Study and modeling of the compressive and splitting tensile strengths of polypropylene fiber reinforced concrete containing recycled asphalt pavement.

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Abstract: In a context of sustainable development and material recycling, the present study aims to study mechanical properties of a recycled asphalt pavement (RAP) concrete, reinforced with polypropylene fibers (PF). First, five formulations were designed with different RAP content with a maximum of 50% at a water cement ratio (W/C) of 0,50. Experimental results showed that the more RAP content increases in mix, the more mechanical strengths decrease, mainly due to the weak interfacial transition zone (ITZ) between the mortar and the recycled material. Reinforcement of PF at 0.1% and 1% volume fraction was realized on all mixes and the experimental results showed that the compressive strength is increased while the splitting strength is decreased. Then, an experimental linear relationship between the splitting tensile strength and the compressive strength is proposed. In the second part of the study, the mechanical strengths were modeled using a factorial plan 2^2, giving a quantification of the individual effect of both introduction of the RAP and the reinforcement and the combined effect, on response in terms of compressive strength and splitting tensile strength. Established model predicted the mechanical strength of a hardened concrete, whatever the RAP content and whatever the PF reinforcement content.

Keywords: environment; sustainable materials; recycled asphalt pavement concrete; recycling; valorization; compressive strength; splitting tensile strength; polypropylene fibers; factorial plan; modeling.

1. Introduction

Cement concrete has become the most popular material nowadays. The main convenient of its spectacular development the huge excessive and continue consummation of natural aggregates which, in long terms, causes ecological disasters. From that moment, it becomes necessary to find the right compromise between the increasing industry demand in aggregate, and the emergency to protect the environment. Hence, new ecological techniques have emerged based on recycling and durability. The most used recycled materials actually used in concrete design are material wastes from buildings demolition and asphalt pavement from bituminous roads (figure 1).

Figure.1 a) Recycled demolition materials [1] b) Recycled asphalt pavement.

Many studies and laboratory investigations about the reuse of demolition waste and asphalt pavement have been presented. Richardson et al. [2, 3] used washed and unwashed aggregate from demolition to make concrete.

They observed an improvement in performances compared to conventional concrete, when a pre-treatment is applied. But the process induces a supplementary cost and time. The more the pre-treatment of recycled materials is strong the better is the quality of obtained concrete. Ait Mohamed Amer et al. [4] studied the influence of the pre-saturation and dry of the recycled aggregates from concrete demolition, on the mechanical and rheological properties of concretes. Authors demonstrated that this process allows keeping reasonable superplasticizer contents and satisfactory rheological parameters. Erdem et al. [5] compared the mechanical properties of concretes made with natural angular aggregates, natural round aggregates, recycled aggregates from demolition and recycled asphalt pavement. An important decrease in mechanical strengths is observed on concretes made with recycled aggregates. Also, authors pointed out that when natural aggregates are used, the failure occurs in the aggregates. When recycled aggregates are used, it occurs in interfacial zone aggregate-mortar. Concerning the fresh properties, the workability is highly affected by the introduction of recycled aggregates. Then, a more important quantity of superplasticizer is needed.

Generally, compressive and splitting tensile strength of concretes made with recycled aggregates is decreased comparing with conventional concretes. The relative loss depends on the water cement ratio and it is most important for low strength class concretes [6] and for content exceeding 30% of recycled materials. The weak interface is located in the transition zone in the old mortar [7]. Indeed, some authors [8] recommended to not exceed 30% of recycled aggregates from demolition. Corinaldesi demonstrated that the relative loss in strengths is more important when coarse natural aggregates were replaced by coarse recycled aggregates hence, compressive strength is not highly affected by the introduction of fine recycled aggregates with contents less than 30% and the splitting tensile strength and the modulus of elasticity are decreased but remained satisfactory with contents less than 30% [9].

About the reuse of recycled asphalt pavement in concretes, Mathias realized complex modulus tests and demonstrated that the rheological behavior of recycled asphalt pavement concrete is similar to conventional concrete [10]. Huang et al. [11] in another side studied four types of recycled asphalt pavement concrete. The first type of concrete is fully made with natural aggregates, the second one is made with coarse recycled pavement aggregate and natural fine aggregates, the third one is made with fine recycled pavement aggregate and coarse natural aggregates, and the last one is fully made with recycled asphalt pavement aggregates. The main conclusions were that recycled asphalt pavement concrete can be confectioned, mixed and mold like a conventional one, and that compressive strength and modulus of elasticity decreases considerably when recycled asphalt pavement are introduced but the toughness index increases. The less relative loss in strengths is observed when coarse natural aggregates are replaced by coarse recycled asphalt pavement.

In aim to improve the durability and strengths on concretes in general and recycled aggregate concrete in particular, some admixtures can be added. Abtahi et al. [12] presented an interesting review about common used fibers added in roads etc. about polypropylene fibers, polyester fibers, cellulose fibers, carbon fibers, glass fibers and nylon fibers. Author pointed out that adding polypropylene fibers in bituminous roads is similar to adding fine aggregate. It increases the fatigue strength, Marshall stability and ductility because of its compatibility with asphalt [13]. There is also basalt fibers which according to their type, increases the pre-failure strength [14].

Polypropylene fibers gained the attention of most researchers, more than the other fibers because of their low cost and their capability to improve the shrinkage-crack strength [15]. The effect of the fibers depend of the type (monofilament or fibrillated), the length, the diameter, and the concrete formula [16]. Indeed, Banthia and Gupta studied the effect of these fibers on shrinkage. Authors recommended long fibers with small diameters for an optimal reduction in cracked surface and crack width, and recommended fibrillated fibers for an optimal reduction of shrinkage cracks.

The combined effect on concrete properties, of polypropylene fibers at 0.2 to 0.5% and silica fume is the improvement of the absorption of kinetic energy, and higher contents of polypropylene fibers associated to low water cement ratios, increase compressive, splitting tensile and flexural strengths, probably due to the pozolanic effect of the silica fume and the capability of the fibers to reduce cracks, and decrease electrical conductivity [17, 18].

In the following part, we will study the compressive and splitting tensile strengths of recycled asphalt pavement concretes. Polypropylene fibers will be added in aim to reduce the relative loss due to the partial replacement of natural aggregates by recycled aggregates. Concretes are made at a constant water cement of 0.5. A modeling is developed using a 2^2 factorial design, predicting the response in terms of compressive strength and then in terms of splitting tensile strength, with influent parameters which are the recycled asphalt pavement content and the polypropylene fibers content.

2. Experiment

Experimental program investigates on the determination of compressive and splitting tensile strengths of a recycled asphalt pavement concretes, made with different contents of substitution of natural aggregates, with a maximum of 50%. Polypropylene reinforcements are at 0.1% (recommended content) and 1% (important content but retained for research purpose) given in volume fraction.

Portland cement CEM IIA/42.5 from Sour El Ghozlane – Bouira (Algeria) is used to produce all mixes. Table 1 shows its chemical composition. Crushed calcareous sand 0/3 and gravels 8/15-15/25 are used, coming from a carry in El Hachimia region-Bouira. Recycled asphalt pavement is provided from a thirty five old road cross Beni Amrane-Boumerdes. The shape of the recycled aggregates is irregular. Graduation curves of natural and recycled aggregates are shown in figure 2. Mechanical properties of aggregates are mentioned in table 2. Polypropylene fibers BELMIX 12 are furnished by AFITEX Algeria which properties are shown in table 3.

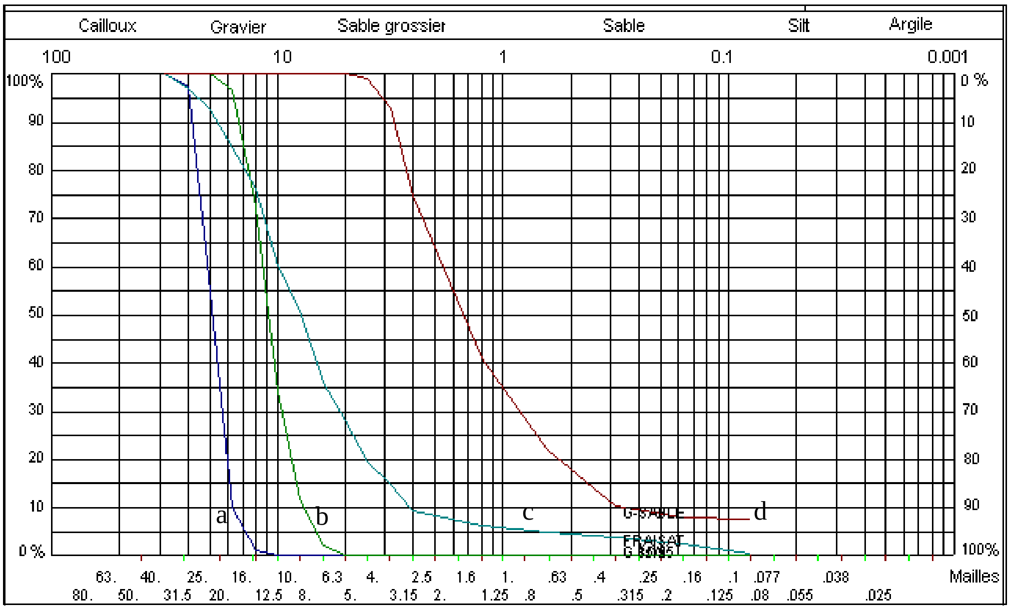

Figure.2 Graduation curves of a) gravel 15/25 b) gravel 8/15 c) RAP d) sand.

Table 1. Cement chemical composition.

Cement	Density (g/cm^3)	Specific surface of Blaine (cm^2/g)	SiO_2(%)	Al_2O_3(%)	Fe_2O_3(%)	CaO(%)	MgO(%)	K_2O(%)	Na_2O(%)	CaO free(%)	C3S clinker(%)
CPJCEM II/A 42.5	3.14	3997	19.38	4.18	3.28	60.55	2.14	0.57	0.18	1.06	59.70

Table 2. Physical and mechanical properties of aggregates.

Content	Sand	G 8/15	G 15/25	RAP
Density (kg/m^3)	2.64	2.64	2.65	2.40
Fineness modulus	3.07	/	/	/
Sand equivalent (%)	80	/	/	/
MDE (%)	/	24	/	37
LA (%)	/	27	22	25
Asphalt content (%)	/	/	/	4.12

Table 3. Physical and mechanical properties of polypropylene fibers

Properties	Polypropylene fibers
Density (g/cm^3)	0.91
Diameter (µm)	34
Length (mm)	12
Modulus of elasticity (MPa)	3750
Geometry	Multifilament
Content	600-900g/m^3

A total of fifteen mixtures were designed as shown in table.4 where the absolute volume method was applied for the partial substitutions. For partial substitutions of natural aggregates with recycled aggregates contents were considered 20-30-40 and 50% (named RAP 20%, RAP 30%, RAP 40% and RAP 50% respectively) and compared to conventional concrete fully made with natural aggregates (named RAP 0%). Considered water cement ratio is 0.50. The same mixtures are designed with polypropylene reinforcement at 0.1 and 1%. Cement content is 330 kg/m^3. Target compressive strength is 20 MPa. The « two steps mixing approach TSMA » [19] was applied during mixing. It should be pointed out, that RAP used has not been treated with the exception of a screening at 20mm.

Table 4. Concrete formulas.

Concrete type	RAP 0%	RAP 20%	RAP 30%	RAP 40%	RAP 50%
Cement (Kg)	330	330	330	330	330
Coarse aggregates (Kg)	1192	952	832	716	596
Fine aggregates (Kg)	704	564	492	424	352
G/S	1.69	1.69	1.69	1.69	1.69
RAP content (%)	0	20	30	40	50
Water (Kg)	168	168	168	168	168
Superplasticizer (Kg)	5.8	9.6	10.2	11.6	14
PF (%)	0-0.1%-1%	0-0.1%-1%	0-0.1%-1%	0-0.1%-1%	0-0.1%-1%

A superplasticizer, from SIKA Algeria, was added to correct the workability of RAP concretes, highly affected by the introduction of the recycled materials, in sufficient quantities to obtain plastic concretes (S3 class). The properties of the product are mentioned in table 5. After the mixing procedure, fresh concrete was placed in cylinders Ø160mmX320mm in three layers and consolidated by using pricking. Specimens were left in their moulds for 48 h and finally cured in water at 20±2°C. Three concrete specimens were prepared for every batch. Tests are conducted at 7-14 and 28 days.

Table 5. Superplasticizer properties.

Content	Superplasticizer
Color	Brown
Density	1.06±0.01
PH	6±1
Na_2O Eq. Content (%)	≤1
Dry extract (%)	30.2±1.3
Cl^- ions content (%)	≤0.1
Recommended content (%)	0,2 à 3 % cement weight

Standard tests for conventional concretes were conducted on specimens because of the similar rheological behavior of RAP concretes compared to conventional concretes [8]. Slump test according to NF P 18-451 [20]. Compressive strength according to NF EN 12390-3 [21]. Splitting tensile strength according to NF EN 12390-6 [22]. Specimens were confectioned according to NF EN 12390-2 [23].

3. Results and discussion

The designed mixtures present the following fresh and hardened properties.

3.1 Fresh properties

Workability is highly affected by the introduction of RAP. Hence, a superplasticizer is added to all mixes in an adequate quantity in aim to obtain a satisfactory workability. The controlled slump is about 90 à 120 ± 15mm. Fresh density varies from 2422.85 kg/m^3 à 2305.75 kg/m^3 when half of natural aggregates are substituted with recycled aggregates. The relative loss in fresh density is only of 4.8%. Similar values are obtained with polypropylene fiber reinforced concretes. In fact, the introduction of polypropylene fibers at 1% do not affect the fresh density either workability.

3.2 Hardened properties

Mechanical properties considered are compressive and splitting tensile strengths. Results tests are given at 7, 14 and 28 days.

3.2.1 Compressive strength

Visual observation of specimens under compression tests show a significant difference between conventional concretes and concretes made with RAP. At failure, conventional concretes cracks suddenly and strongly while RAP concretes present a less strong and less brutal failure, visible cracks are formed clearly before failure as shown in figure 3. This phenomenon is the more apparent, the more the RAP content is important in mix. Compressive test results are reported in table 6.

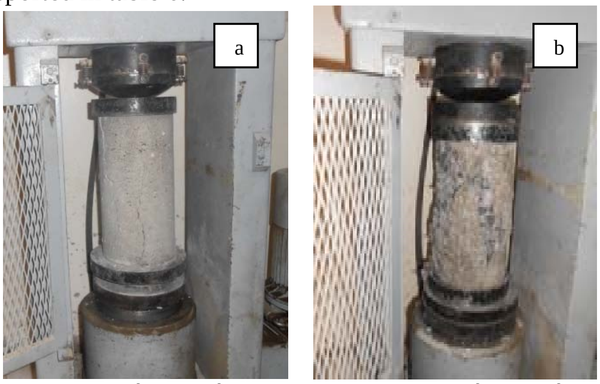

Figure 3. Compressive test a) failure of conventional concrete b) failure of 50% RAP concrete.

Table 6. Experimental compressive strength results.

	PF (%)	7 days	14 days	28 days
RAP 0%	0	13.64	17.32	19.19
RAP 20%		12.18	15.73	17.19
RAP 30%		11.28	13.75	15.68
RAP 40%		9.12	11.79	13.03
RAP 50%		7.63	9.55	10.38
RAP 0%	0.1	14.80	18.63	20.14
RAP 20%		12.86	16.62	18.07
RAP 30%		11.84	14.75	16.73
RAP 40%		9.91	11.42	13.97
RAP 50%		8.06	10.30	10.70
RAP 0%	1.0	17.19	20.79	22.27
RAP 20%		14.92	17.71	20.67
RAP 30%		13.48	16.88	18.58
RAP 40%		10.67	14.49	15.86
RAP 50%		9.41	10.71	12.69

In aim to better see the evolution of compressive strength in function of RAP content and PF content, results at 28 days of age are graphically represented on figure 4.

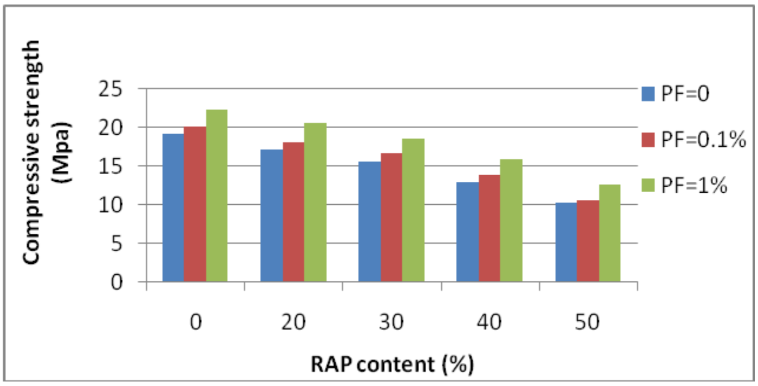

Figure. 4 Compressive strength test results at 28 days.

For the non reinforced concretes, an important relative loss in compressive strength is observed when the RAP content increases in mix. Obtained results are in accordance with most works reported in literature. The more RAP content in mix increases, the more compressive strength decreases. Experimental results show that relative loss in compressive strength due to the RAP introduction is only of 10% for RAP 20% at 28 days. It is an important result because, a priori, 20% of RAP can replace natural aggregate with a minimal impact on compressive strength. The relative loss is about 46% for RAP 50% at 28 days traducing approximately that compressive strength decreases to the half value when half natural aggregates are substituted with RAP. Similar values are obtained with other mixtures. Relative loss is about 11% for RAP 20% comparing to conventional concretes at 7 days. It is about 17% for RAP 30% and reaches 44% for RAP 50%. Again, intermediary values are obtained with other mixtures at 14 days.

The decrease in strength can be explained by the weak adhesion between the old bituminous surface of the recycled material and mortar; at the weak ITZ as reported generally in literature about recycled aggregate concrete.

When PF are added at 0.1% content, the compressive strength is increased but not very significantly, for RAP concretes as well as conventional concretes. At 7 days, relative gain is about 8% for conventional concretes and 5% for RAP 50%. At 28 days, relative gain is about 5% for conventional concretes and 3% for RAP 50%. Similar values are obtained with other mixtures.

The effect of PF introduction is clearer with higher content. At 1%, the compressive strength is significantly increased. At 7 days, relative gain is about 26% for conventional concretes and 23% for RAP 50%. At 28 days, relative gain is about 16% for conventional concretes and 22% for RAP 50%. Similar values are obtained with other mixtures. Again, similar values are obtained with other mixtures.

3.2.2 Splitting tensile strength

Test results are reported in table 7.

Table 7. Experimental splitting tensile strength.

	PF (%)	7 days	14 days	28 days
RAP 0%	0	1.71	1.90	2.21
RAP 20%		1.52	1.80	2.08
RAP 30%		1.43	1.69	1.83
RAP 40%		1.31	1.47	1.68
RAP 50%		1.19	1.30	1.38
RAP 0%	0.1	1.76	1.95	2.17
RAP 20%		1.44	1.71	2.11
RAP 30%		1.34	1.57	1.78
RAP 40%		1.26	1.43	1.60
RAP 50%		1.22	1.33	1.41
RAP 0%	1.0	1.43	1.62	1.85
RAP 20%		1.30	1.57	1.77
RAP 30%		1.27	1.42	1.63
RAP 40%		1.10	1.26	1.45
RAP 50%		1.00	1.12	1.33

In aim to better see the evolution of splitting tensile strength in function of RAP content and PF content, results at 28 days of age are graphically represented on figure 5.

For non reinforced concretes, splitting tensile strength decreases the more RAP content in mix increases, but not as dramatically as for compressive strength. Indeed, at 28 days, relative loss is only about 6% for RAP 20%. It is 17% for RAP 30% and reaches 38% for RAP 50%. At 7 days, relative loss is about 11% for RAP 20% comparing to conventional concrete. It is 16% for RAP 30% and reaches 30% for RAP 50%. Intermediary values are obtained for other mixtures at 14 days. The decrease in splitting tensile strength can be explained as for compressive strength, by the weak ITZ.

When PF are added at 0.1%, the effect on splitting tensile strength is not very clear, for RAP concrete, as well as for conventional concretes. Hence, it is not possible to express a tendency to traduce the effect of PF reinforcement. It is in accordance with Alhozaimy et al. [24].

When PF are introduced at 1%, a significant decrease in strength is observed in all mixes. Relative loss at 28 days reaches 16% for conventional concretes, and 28% for RAP 50%. Similar values are obtained for other mixes at14 and 28 days.

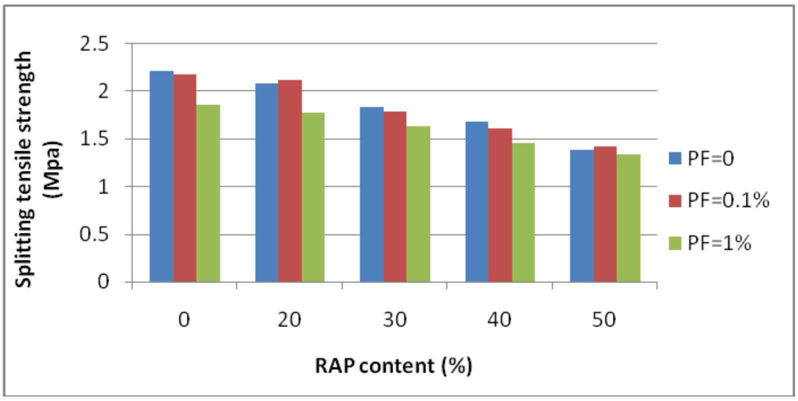

Figure. 5 Splitting tensile strength test results at 28 days.

4. Experimental relationship between compressive and splitting tensile strength

In order to better evaluate the dependency of splitting tensile strength on compressive strength, the relationship between strengths, in case of non reinforced concrete and slightly reinforced, and in case of strongly reinforced concretes, is shown in figure 6. It appears clearly that a good correlation is obtained, as it is indicated by the coefficient of determination R^2. Most statisticians consider that a model is acceptable and satisfactory for a coefficient 0.70 and higher [25].

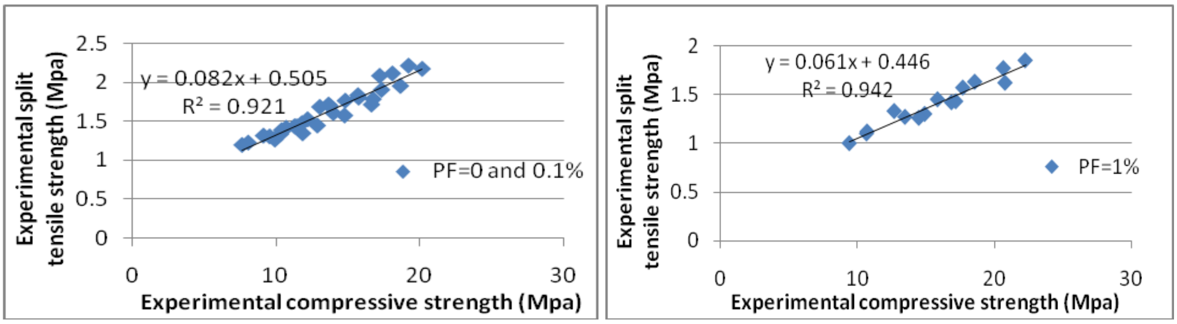

Figure. 6 Experimental relationship between compressive and splitting tensile strength.

Splitting tensile strength, as well as compressive strength, is affected by the type of aggregates used, water cement ratio, time of cure and dimension of tested specimens [26, 27]. Mechanical strengths are affected by the type, shape and geometry of the fibers (length, diameter) and content. However, proposed relations are given only in function of the compressive strength, based on small number of experiment data. Hence, more research is needed to verify these relations, as a complement investigation.

5. Modeling

In aim to estimate and quantify the effect of RAP and PF introduction, on compressive and splitting tensile strengths of a hardened concrete, a factorial design was developed, and a mathematical model was built. The established model predicts mechanical strengths at 28 days of age. Generally, factorial designs need a variable change when lowest levels are designated by -1 and highest levels by +1. Then, centered or coded variables are handled. High and low levels of all considered factors, delimit the field of the study. Factorial designs are most of the time presented with a statistical study of the experimental results, with a validation step, the estimation of the experimental error and confidence interval [28].

From experimental test results, a factorial design 2^2 has been build in order to model the compressive strength and then splitting tensile strength in terms of influent factors; RAP content and PF content. The study of the effect of the influent parameters is considered separately, for every mechanical strength.

The interval of RAP content used in this study is [0, 50%]. It was cut into five experimental fields; [0-30%] noted field I, [30%-50%] noted field II, [20%-40%] noted field III, [0-40%] noted field IV and [0-50%] noted field V. For each field, RAP content and PF content values take minimal coded variables for minimal natural values and maximal coded variables for maximal natural values.

A polynomial model is chosen to quantify the effect, on response in terms of compressive strength first, and then in terms of splitting tensile strength, of RAP content a1, of PF content a2 and of the combined effect of both parameters a12, according to the following expression:

$$Rc = a0 + a1\ X1 + a2\ X2 + a12\ X1\ X2 \quad (1)$$

And

$$Rf = a0' + a1' X1 + a2' X2 + a12' X1X2 \quad (2)$$

Where Rc is the compressive strength, Rf is the splitting tensile strength, X1 coded variable related to RAP content, X2 coded variable related to polypropylene fibers and a0, a1, a2, a12 are the polynomial coefficients. Mathematical resolution of established equations gives the polynomial coefficients for five experimental fields. Results are mentioned on table 8.

Table 8. Polynomial coefficients values.

Field	a0	a1	a2	a12	
[0-30%]	18.93	-1.8	1.495	-0.045	Compressive strength
[30-50%]	14.3325	-2.7975	1.3025	-0.1475	
[20-40%]	16.6875	-2.2425	1.5775	-0.1625	
[0-40%]	17.5875	-3.1425	1.4775	-0.0625	
[0-50%]	16.1325	-4.5975	1.3475	-0.1925	
	a0’	a1’	a2’	a12’	
[0-30%]	1.88	-0.15	-0.14	0.04	Splitting tensile strength
[30-50%]	1.5425	-0.1875	-0.0625	0.0375	
[20-40%]	1.745	-0.18	-0.135	0.02	
[0-40%]	1.7975	-0.2325	-0.1475	0.0325	
[0-50%]	1.6925	-0.3375	-0.1025	0.0775	

Results show that individual effect of RAP introduction on compressive strength is negative and similar whatever the considered field, while the individual effect of PF introduction is positive. However, the combined effect of both parameters is smaller the individual effect and it is negative for all fields.

However, results show that individual effect of RAP introduction on splitting tensile strength is negative and similar whatever the considered field. The individual effect of PF introduction is negative too. However, the combined effect of both parameters remains positive for all fields.

It is noticed, concerning compressive strength, that the negative individual effect of RAP introduction on response is minimal in field I for RAP percentages between 0 and 30%. The positive individual effect of PF reinforcement on response is maximal in field III for RAP percentages between 20 and 40%.

Concerning splitting tensile strength, the negative individual effect of RAP introduction on response is minimal in field I for RAP percentages between 0 and 30%. The negative individual effect of PF reinforcement on response is minimal in field II for RAP percentages between 30 and 50%.

An optimal content of RAP can be recommended: it is about 30%.

Retained mathematical models predict compressive and splitting tensile strength in function of RAP content and PF content, of 28 days aged concretes, as follow:

$$Rc = 17.81 - 2.02\ X1 + 1.54\ X2 - 0.1\ X1X2 \quad (3)$$

With mean values of obtained polynomial coefficients in fields I and III.

$$Rf = 1.71 - 0.17\ X1 - 0.10\ X2 + 0.04\ X1X2 \quad (4)$$

With mean values of obtained polynomial coefficients in fields I and II.

Statistical analysis of experimental results, with validation tests in the center of each field and for all cure time, leads to an experimental error less than 10%.

6. Conclusion

The main conclusions that can be drawn are the following:

1) Workability of concrete is highly affected by the introduction of RAP while the reinforcement with PF does not affect fresh properties.

2) For non reinforced concretes, relative loss in compressive strength due to RAP introduction is only 10% when 20% of natural aggregates are replaced by recycled asphalt pavement aggregates. It reaches 46% when half of natural aggregates are replaced, at 28 days.

3) Adding PF increase significantly compressive strength. At 1% reinforcement, gain is about 16% for conventional concretes and 22% for RAP 50% concretes, at 28 days. But increasing in compressive strength is in detriment of splitting tensile strength. Indeed, relative loss in splitting tensile strength due to PF introduction is about 16% for conventional concretes and reaches 28% for RAP 50% concretes.

4) A simple linear experimental relationship between splitting tensile strength and compressive strength is established, in case of non reinforced and slightly reinforced concretes and in case of strongly reinforced concretes, with important coefficients R^2. It gives a good estimation of concrete splitting tensile strength only from its compressive strength.

5) Modeling mechanical strengths using 2^2 factorial designs, permits to quantify individual and combined effects of RAP and PF introduction on response in terms of compressive strength then in terms of splitting tensile strength.

6) An optimization in RAP content can be recommended by minimizing the negative effect of RAP introduction and maximizing the effect of PF introduction; it is 30% RAP.

7) Mathematical model established predicts both compressive and splitting tensile strengths of concretes, whatever RAP content introduced and whatever PF reinforcement. Presented results are available for courant 20 MPa concrete. Further studies must be conducted this way to include higher concrete strength classes.

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