EFFECTS OF SUPERPLASTICIZER ADMIXTURE ON THE MECHANICAL BEHAVIOUR OF LIGHTWEIGHT CONCRETE MIXES CONTAINING MINERAL ADDITIVES

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ABSTRACT

This paper presents an experimental investigation of the effect of a superplasticizer admixture on the mechanical behaviour of expanded clay lightweight concrete containing metakaolin material and recycled glass aggregate. The optimum dosage of the superplasticizer admixture (type SNF) was adjusted and used by weight of cement. The short and long-term mechanical properties of concrete mixes were measured in accordance with the relevant British / EN standards. The obtained results were compared with the results of control concrete mixes (without superplasticizer).

The results obtained showed that the superplasticizer admixture exhibited a 20% reduction in content of mixing water. All measured values of unit weight, compressive and splitting tensile strengths increased when the superplasticizer admixture is used. The concrete mix containing 30% recycled glass revealed an increase in the mechanical strength compared with the mix of 15% recycled glass. However, the workability of the superplasticizer concrete mixes was degraded, reaching 44% reduction in slump value.

Keywords: Superplasticizer admixture, lightweight aggregate concrete, metakaolin, recycled glass, mechanical behaviour**.**

تأثير الملدن المتفوق على التصرف الميكانيكي للخرسانة الخفيفة الوزن والحاوية على المضاف المعدني

الخلاصة:

يستعرض هذا البحث دراسة عملية للتحري حول تاثير الملدن المتفوق على السلوك الميكانيكي لخرسانة الطين المتمدد الحاوية على مادة الميتاكولين والركام الناتج من تدوير مخلفات الزجاج. النسبة المثلى من الملدن المتفوق تم ضبطها وأُستخدمت كنسبة من وزن الاسمنت. الخصائص الميكانيكية القصيرة والبعيدة الامد تم قياسها للخلطات الخرسانية بالاعتماد على المواصفات القياسية البريطانية. النتائج المستحصلة قورنت مع تصرف الخلطات القياسية (غير الحاوية على مضاف الملدن المتفوق).

أظهرت النتائج المستحصلة إن الملدن المتفوق يبدي 20% نقصان في كمية ماء الخلط. كل الاختبارات الخاصة بقياس وحدة الوزن، مقاومة الانضغاط ومقاومة شد الانشطار اظهرت زيادة في قيم هذه الخصائص عند استخدام الملدن المتفوق. الخلطة الخرسانية الحاوية على 30% ركام الزجاج المدور أظهرت نتائج اعلى منها للخلطة الخرسانية الحاوية على 15% ركام الزجاج المدور. على كل حال، القابلية التشغيلية للخلطات الحاوية على مضاف ملدن تاثرت حيث وصلت الى نقصان مقداره 44%.

1 INTRODUCTION

Improving the mechanical strength of lightweight concrete has recently been the subject of many published research into construction materials. Environmental criteria have been also considered with regard to reducing the impact of waste disposal in land fill by reusing these waste and by-product materials as construction materials [1].

One of the main techniques which has been used in developing the strength of concrete is the use of admixtures. The superplasticizer SP (also known as high range water reducer) is often used in both the concrete industry and on construction sites.

Different kinds of superplasticizer admixtures are available. They have similar conjunction roles in triggering dispersive action on the surface of hydration cement particles during the initial hydration reactions [2]. The active ingredients of these products are commonly based on an anionic polymeric surfactant [3]. The molecules of superplasticizer coat the cement grains and change their orientation, causing them to repel one another [4]. Two contrasting properties can be achieved with a superplasticizer admixture: either an increase in workability, combined with retention of the strength level, or the opposite. The superplasticizer action causes re-arrangement of the cement particles, resulting in more regular and allowing better hydration.

Several models have been suggested to explain the effect mechanism of superplasticizer on the cement hydration process [2]. One of these models is the adsorption mechanism which attributes the effectiveness of the superplasticizer to the adsorption behaviour of the admixture on the cement particles. It was proposed that the elementary processes were based on both adsorption and desorption [5]. Another study reported that the superplasticizer was capable of reducing the surface tension of water. This permits penetration of the molecules in between the solid particles and produces much denser mixes, which consequently reduces the tendency of permeable water [6].

The results of fluidising due to use of superplasticizer admixtures are affected by several parameters: for example, dosage of the superplasticizer; type and quantity of aggregate and cement used; mixing procedure and temperatures [7].

A growing number of alternatives to the traditional ingredients of concrete mixes have surfaced in recent years. This is as a consequence of the need to reduce the demand on natural resources created by construction materials. One of these alternative materials is recycled glass aggregate. It has been used as an entire or partial replacement for both fine and/or coarse aggregate [8-12]. This approach is useful to mitigate the impact of waste glass which is produced in large amounts every year.

The inclusion of glass aggregate in concrete mixes causes an increase in the expansion phenomena due to the alkali–silica reaction (ASR) produced [8-16]. However, this reaction can be reduced by using mineral additives [8, 16]. Metakaolin (MK) is an example of such a mineral by-product materials. It has a higher pozzolanic ratio and is used as a partial replacement for cement, and has received considerable interest for its applications to construction. The main effects of using metakaolin are the improvement of the strength and durability of concrete mixes [17-24].

An attempt to develop the mechanical strength of a newly modified lightweight concrete using a superplasticizer admixture in conjunction with metakaolin was experimentally investigated in this study. This type of lightweight concrete contains different ratios of recycled glass and uses expanded clay as a coarse aggregate.

2 EXPERIMENTAL DETAILS

2-1. Materials

The main ingredients of the concrete mixes were ordinary Portland cement, natural sand, expanded clay, recycled glass, metakaolin and superplasticizer admixture. Locally available ordinary Portland cement complying with the Iraqi Standard No.5 [25] was used in this study.

Natural sand for building purposes was used as a fine aggregate with a grading which complied with BS EN 12620[26]. A medium-grade 8-5R of Techni Clay expanded clay was used as coarse aggregate. The moisture content and particle density of the expanded clay were 20% w/w and 550 kg/m3 respectively.

Recycled glass aggregate with particle sizes of 0.5-1 and 1-2 mm was used as a partial replacement for natural sand by volume with two levels: 15% and 30%. MetaStar 501metakaolin material [28] with a constant content (10%) was adopted as a partial replacement for ordinary Portland cement.

The Daracem SP6 superplasticizer admixture of the sulphonated naphthalene formaldehyde condensate SNF [29] was used throughout this study, its performance complies with BS EN 934-2[30]. It's maximum chloride and alkali contents were < 0.1% and 0.5% by mass respectively.

The mixing operation was carried out according to BS EN12390-2 [31]. The fresh concrete was cast in moulds in three layers; each layer was completely compacted. After casting, the samples were kept in laboratory conditions and covered with a nylon sheet to ensure a humid atmosphere around the specimens. After 24 hours, the samples were demoulded, marked and immersed in a basin of water at a temperature of 20 ± 2 ˚C until the date of the test.

2-2. Selection of the superplasticizer content

In this experimental programme, the workability of the concrete mixes was kept constant, while the strength level was intended to be increased. On this basis, the content of the superplasticizer was adjusted based upon the fluidity features of the reference lightweight concrete mix (0% G+0%SP+0%MK), which possesses a W/C of 0.45. In order to maintain a constant slump (50± 5 mm), multi-trial mixes were carried out and the W/C resulting from using the superplasticizer admixture was calculated each time according to the following equation [32]:

$$\mathrm{W/C\ of SP_{mix}} = \mathrm{W/C\ of R_{mix}} \times \frac{(100 - \text{percentage water reduction})}{100} \qquad (1)$$

where $\mathrm{SP_{mix}}$ and $\mathrm{R_{mix}}$ are, respectively, the concrete mix containing superplasticizer and the reference concrete mix .

Since the experimental work scheme was concerned with improving the mechanical strength of the concrete mixes, it was found that 2% superplasticizer by weight of cement was the optimum admixture dosage. This dosage produced higher compressive strength (19.7 MPa at 28 days age) with a maximum water reduction of 20%, equivalent to a W/C of 0.36.

In accordance with these results the optimum superplasticizer content was chosen to produce two modified concrete mixes containing expanded clay, recycled glass and metakaolin materials (superplasticizer mixes). The measured mechanical properties of the former mixes were then compared with concrete mixes with the same constituents without superplasticizer (control mixes).The details of the concrete mixes which were adopted in the experimental programme are shown in Table 1.

2-3. Test programme

The experimental programme tests included studying the fresh properties, unit weight, compressive strength, splitting tensile strength and stress-strain behaviour. All of these tests were conducted according to the relevant BS / EN standards [33-36].

The short and long-term mechanical properties of the concrete mixes were experimentally measured. Except for the stress-strain behaviour test which was carried out using two cylindrical specimens, an average value of three specimens was taken for each test result.

3 RESULTS AND DISCUSSION

3.1 Properties of fresh concrete mixes

The behaviour of the fresh status of the concrete mixes in terms of consistency was carried out using a slump test; the obtained results are shown in **Figure 1**. It can be seen that the workability aspect was degraded when the superplasticizer was used in producing the modified concrete mixes. A clear decrease in the value of the slump was recorded for both superplasticizer mixes, and further compaction work using a poker vibrator was required to overcome the drying condition of these mixes. This could be due to the accelerating effect of superplasticizer admixture, which becomes more effective in the presence of metakaolin material. In turn, this causes rapid hydration of the cement particles and reduces the fluidity time of the concrete mixes. The same cannot be said for the control mixes, where the consistency was still found to be within the acceptable range of workable concrete (50±5 mm). However, the concrete mixes with a glass content of 30% showed a lower reduction in the workability aspect than that of the mixes with 15% glass content. Such behaviour can be attributed to the role of the glass particles in providing extra moisture content for the concrete due to their adsorbing the mixing water [8-16].

3.2 Unit weight

Figure 2 shows the test results of unit weight for the control and superplasticizer concrete mixes at different test ages. The superplasticizer concrete mixes exhibited higher densities than the control mixes. This may be related to the penetration of the superplasticizer fluid and coating of the solid particles, thereby producing a denser mix [6]. The concrete mixes containing 30% glass ratio showed higher densities than those of the samples with 15% glass ratio. This may be attributed to the capability of these mixes to hold the water particles due to the lower tendency of the glass aggregate to absorb the mixing water [8-16].

In general, except at 28 days' age, both the superplasticizer and the control lightweight aggregate concrete mixes exhibited a continuous decrease in density over time. This behaviour may be caused by two phenomena: the first is the consumption of water by hydration processes and the second is the reduction of free water inside gel pores by evaporation. The increase in density of the concrete mixes at age of 28 days compared with their density at 7 days could be explained by the greater level of hardness due to the pozzolanic reaction of the metakaolin material at this age. Furthermore, acceleration of the cement hydration process can be accounted by the presence of the superplasticizer which provides better water distribution for the cement particles.

3.3 Compressive strength

The compressive strength test results are presented in **Figure 3**. This figure indicates that the superplasticizer concrete mixes possess higher compressive strength values than the control mixes. This result is in agreement with previous studies [1-7]. Furthermore, the presence of metakaolin material, which is a mineral admixture, plays a role in increasing the compressive strength in conjunction with the superplasticizer admixture. The main significance of the induction of metakaolin material are its role as a filler and, an accelerator for the hydration of Portland cement, as well as its pozzolanic properties [17-18]. For the superplasticizer concrete mixes, the concrete mix containing 30% glass produced a higher compressive strength value than that of the mix with 15% glass content. This can be explained by more water being available inside this mix which allows further hydration processes to take place.

For all of the concrete mixes, the compressive strength value increased with increased curing time. The percentage increases in compressive strength for the concrete mixes containing the superplasticizer admixture with 15% and 30% glass ratios at an age of 90 days relative to the control concrete mixes of the same age were 4% and 8.5 % respectively.

Satisfactory failure modes were observed for all concrete samples after the compressive strength test had been conducted which comply with BS EN12390-3[35] mode-A. All four exposed faces were cracked approximately equally, with a little damage to the faces in contact with the platens without any explosive failure, **as shown in Figure 4**.

The pozzolanic reactivity of metakaolin material which, is described in BS EN 196-5[37] was measured according to the values of compressive strength as in [20]. This was done by comparing with the results of reference mix (0%G+ 0% MK+ 0% SP). The same approach also used to predict the pozzolanic reactivity of metakaolin in conjunction with the superplasticizer admixture on the strength of the concrete. The specific strength ratio $R,$ which is an indicator of the contribution of the mineral admixture and/or the superplasticizer to the strength of the mixture is defined as:

$$R = f_c/p \qquad (2)$$

where f_c is the compressive strength in MPa and p is the hydraulic cement of mineral and/or superplasticizer admixture percentage. By eliminating the reduction effect of the glass aggregate on the values of compressive strength, the contribution of the pozzolanic effect of metakaolin and/or superplasticizer R_p to the strength of concrete is given by Eq. 3.

$$R_p = R_M - R_C \qquad (3)$$

where $R_M$is the contribution of unit hydraulic cement when metakaolin and/or superplasticizer is used and R_C the contribution of unit hydraulic cement to the concrete strength without using metakaolin and/or superplasticizer.

The index specific strength $K,$ is the ratio of R_M to R_C . The contribution of pozzolanic effect and/or superplasticizer P to the concrete strength can be expressed as:

$$P = (R_P/R_M) \times 100 \qquad (4)$$

The values of R, R_p, K and P for the reference, control and superplasticizer concrete mixes at ages of 7,28, 90 and 180 days were calculated and are presented in **Table 2**.

The contribution of metakaolin and the superplasticizer admixture to the compressive strength of the concrete was plotted in **Figure 5**. For both control concrete mixes, the improvement in compressive strength due to the pozzolanic effect of metakaolin exhibited a long-term duration (180 days).This is in agreement with the results of [38]. The optimum activity was recorded at 90 days age. The combined effect of metakaolin and superplasticizer was clearer in the earlier ages and reached its peak performance at 28 days age with a ratio of 30% contribution to the compressive strength. Thereafter, a reduced effect was observed.

3.4 Splitting tensile strength

Figures 6 and 7 show the test results of splitting tensile strength at sample ages of 120 and 180 days. These figures showed increase in splitting tensile strength for the superplasticizer concrete mixes relative to that of the controlled mixes. This could be attributed to an increase in compressive strength of these mixes, resulting from the positive action of superplasticizer admixture with metakaolin. Behaviour consistent with that of compressive strength was recorded for both test ages. When compared with the controlled concrete mixes, the percentage increases in the splitting tensile strength of the superplasticizer concrete mixes containing 15% and 30% recycled glass at 120 days age were 9.4% and 11% respectively. The corresponding percentages at 180 days age were 7% and 21.3% respectively.

BS EN 1992-1-1[37] suggested the following expression to predict the splitting tensile strength of lightweight concrete according to its density and the characteristics of normal weight concrete.

$$f_{lctm} = f_{ctm} \cdot \eta_1 \tag{5}$$

$$f_{ctm} = 0.3 \times f_{ck}^{2/3} \tag{6}$$

$$\eta_1 = 0.4 + 0.6\rho/2200 \tag{7}$$

where f_{lctm} and f_{ctm} are the splitting tensile strength of the light and normal weight concrete respectively in MPa ; f_{ck} is the compressive strength of normal weight concrete in MPa, and ρ is the density of lightweight concrete in kg/m^3.

After statistical analysis had been performed, it was shown that Equation (5) was unable to match the results obtained for splitting tensile strength in this study. This is because a reasonable R squared value for the nonlinear regression analysis could not be achieved.

4 CONCLUSIONS

The results of this study highlight the effect of superplasticizer admixture when used in conjunction with metakaolin and glass aggregate on the mechanical behaviour of expanded clay concrete. The main conclusions of this paper can be summarized as follows:

- The superplasticizer admixture reduced the water content by up to 20%. However, the workability of the concrete mixes deteriorated with the use of superplasticizer.
- An increase in the density values of the superplasticizer concretes was recorded compared with the controlled mixes, and the highest value was for the mix of 30% glass with 2% superplasticizer admixture for all test ages.
- A significant increase in the compressive strength values was achieved when the superplasticizer admixture was used in conjunction with metakaolin, especially at earlier sample ages.
- Increases in compressive strength due to the pozzolanic effect of metakaolin continued long- term (180 days) for both control concrete mixes.
- The contribution metakaolin and superplasticizer admixture to the compressive strength was clearer at the earlier stages and reached its peak performance at 28 days age with a ratio of 30%.
- Consistent positive improvements in splitting tensile strength to that in compression features were observed at both short and long-term behaviours.

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Table (1): Details of concrete mixes

Ingredient	Concrete mixes				
		Control mixes		Superplasticizer mixes	
	Reference	15% G+0% SP	30% G+0% SP	15% G+2% SP	30% G+2% SP
O. P cement	392.07	352.84	352.84	352.84	352.84
Metakaolin	0.00	39.20	39.20	39.20	39.20
Natural sand	598	508.28	418.59	508.28	418.59
Glass aggregate. 0.5-1	0.00	43.46	86.93	43.46	86.93
Glass aggregate. 1-2 mm	0.00	43.46	86.93	43.46	86.93
Expanded clay	247.50	247.50	247.50	247.50	247.50
Superplasticizer	0.00	0.00	0.00	7.05	7.05
W/C	0.45	0.45	0.45	0.36	0.36

Table (2): Calculated values of $\boldsymbol{R}$, $\boldsymbol{R_p}$, $\boldsymbol{K}$ and $\boldsymbol{P}$ for controlled and modified concrete mixes

Mix name	Age of test	f_c	R	R_p	K	P(%)
Reference mix (0% MK+ 0% SP)	7 days	16.060	0.160	0.000	1.000	0.000
	28 days	18.530	0.1853	0.000	1.000	0.000
	90 days	19.930	0.1993	0.000	1.000	0.000
	180 days	20.800	0.208	0.000	1.000	0.000
Control mix 15% glass 10% MK+ 0% SP	7 days	15.450	0.171	0.011	0.962	6.446
	28 days	19.930	0.221	0.036	1.075	16.322
	90 days	22.070	0.245	0.045	1.107	18.726
	180 days	22.750	0.252	0.044	1.093	17.714
Control mix 30% glass 10% MK+ 0% SP	7 days	15.270	0.169	0.009	0.950	5.343
	28 days	19.820	0.220	0.034	1.069	15.857
	90 days	22.040	0.244	0.045	1.105	18.616

	180 days	22.040	0.244	0.036	1.059	15.063
Superplasticizer mix 15% glass 10% MK+ 2% SP	7 days	18.105	0.205	0.045	1.127	21.939
	28 days	22.835	0.259	0.074	1.232	28.590
	90 days	22.940	0.260	0.061	1.151	23.546
	180 days	22.640	0.257	0.049	1.088	19.151
Superplasticizer mix 30% glass 10% MK+ 2% SP	7 days	19.650	0.223	0.062	1.223	28.077
	28 days	23.480	0.266	0.081	1.267	30.551
	90 days	23.935	0.271	0.072	1.200	26.724
	180 days	25.210	0.286	0.078	1.212	27.393

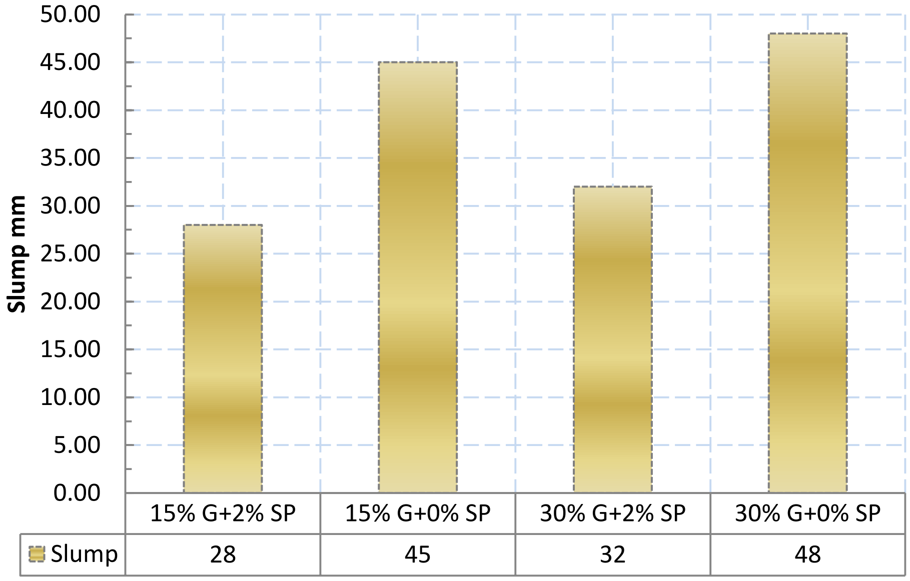

Figure (1): The workability behaviour of various lightweight concrete mixes.

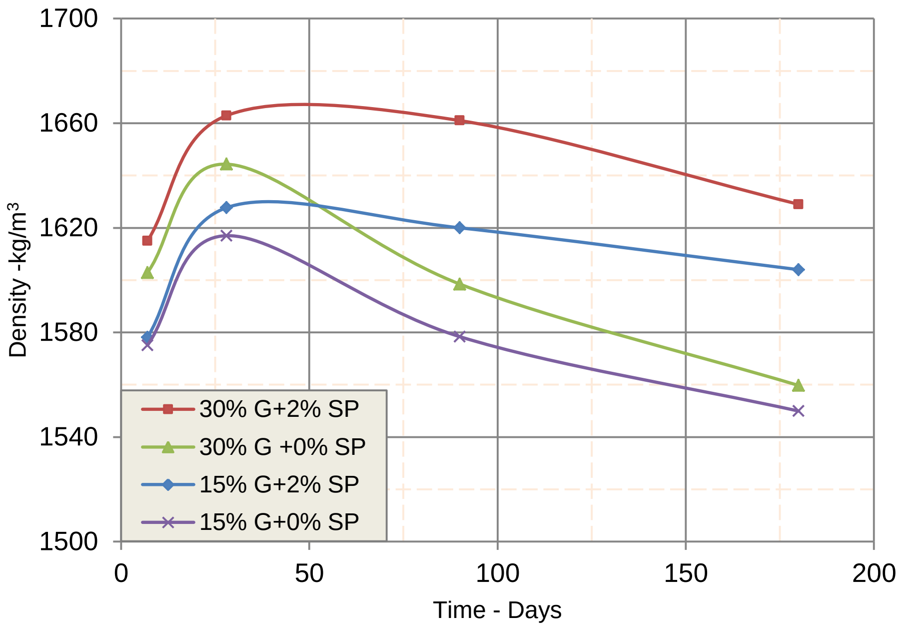

Figure (2): The density of various lightweight concretes mixes.

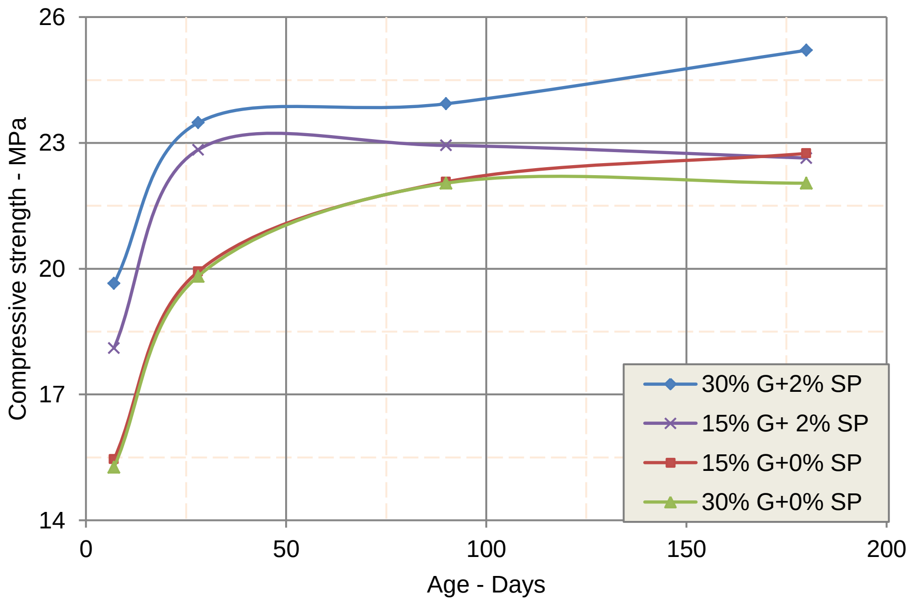

Figure (3): Compressive strength behaviour of various lightweight concrete mixes

Figure (4): Satisfactory compression failure modes [35]: A- Cracks failure, B- Damage failure and C-Explosive failure

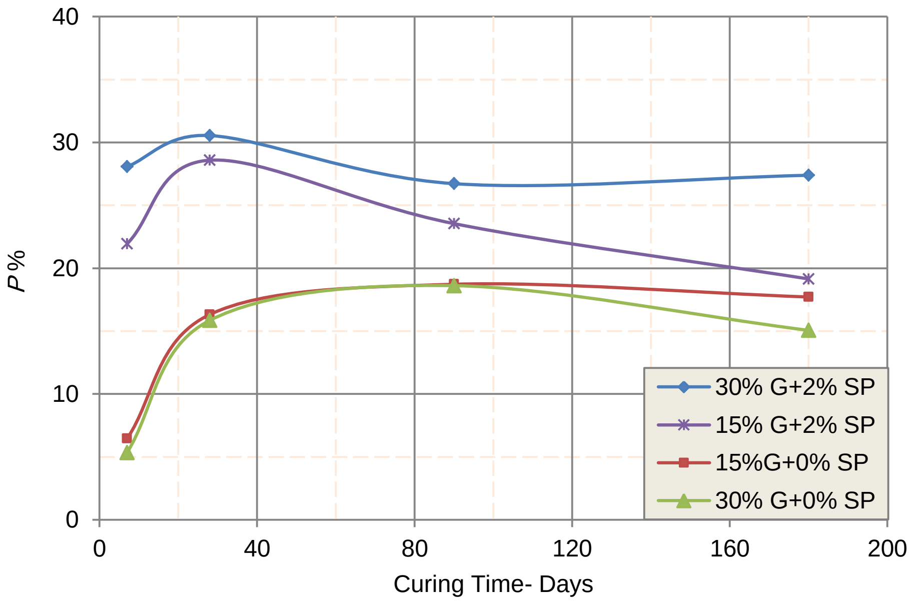

Figure (5): Contribution of pozzolanic effect and/or superplasticizer to the compressive strength of concrete mixes.

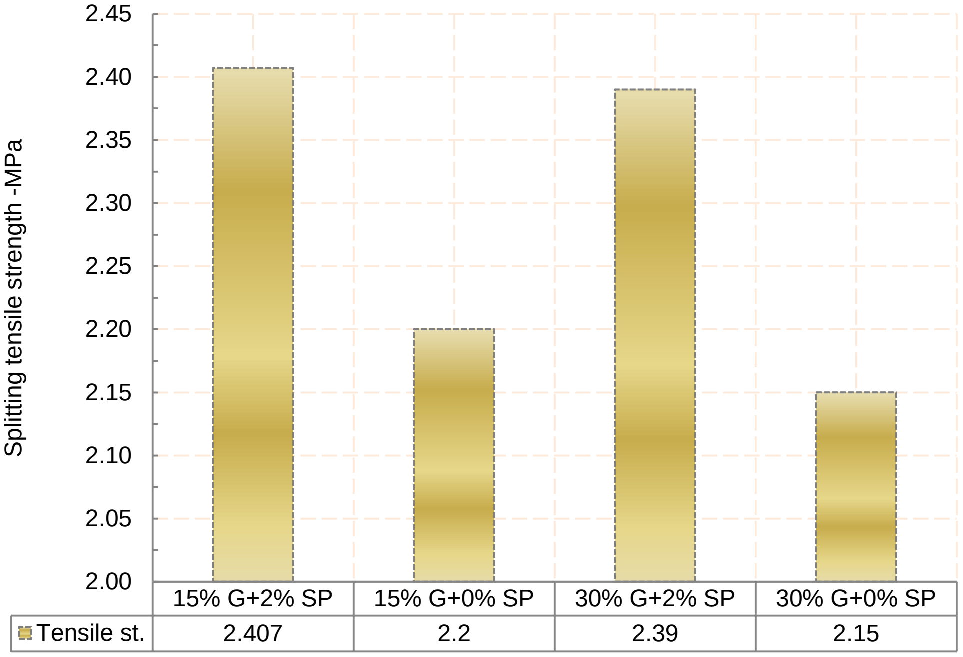

Figure (6): Splitting tensile strength of superplasticizer and controlled mixes

at 120 days

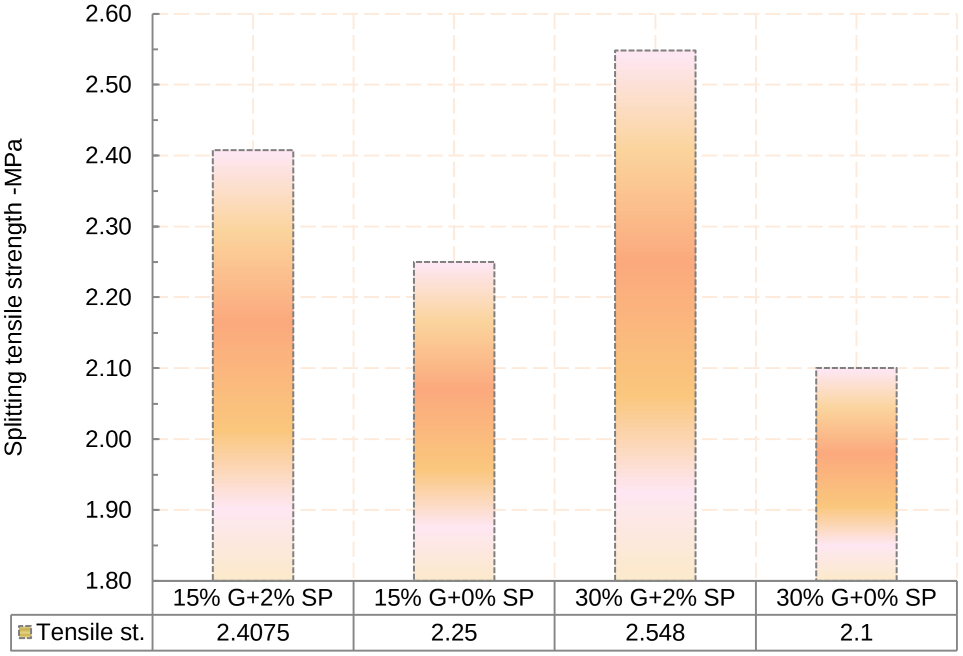

Figure (7): Splitting tensile strength of superplasticizer and controlled mixes at 180 days