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Compressive strength of cement stabilizations containing recycled and waste materials

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Research Paper

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Compressive strength of cement stabilizations containing recycled and waste materials

This study analyses the possibilities of using up to 30% of reclaimed asphalt pavement as a substitute material for natural aggregate, along with fly ash replacing 20% or 40% of Portland cement in cement stabilizations with 4% and 6% of binder. The Proctor test was used to determine maximum dry density and optimal moisture content of cement-based stabilizations. The compressive strength was tested after 7, 28, and 90 days. Parameters influencing 28-day compressive strength were evaluated by full factorial design and by classification in strength classes. The results obtained justify the utilisation of waste and recycled materials in pavement structures.

Key words:
cement stabilization, fly ash, reclaimed asphalt pavement, compressive strength

Prethodno priopćenje

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Tlačna čvrstoća cementnih stabilizacija koje sadržavaju reciklirani i otpadni materijal

U ovom radu analizirane su mogućnosti upotrebe recikliranog asfaltnog kolnika za zamjenu prirodnog agregata do 30 %, zajedno s primjenom letećeg pepela za zamjenu 20 % ili 40 % portland cementa u cementnim stabilizacijama sa 4 % i 6 % veziva. Proktorov pokus je upotrebljen za određivanje maksimalne suhe zapreminske mase i optimalnog udjela vlage u stabilizacijama na bazi cementa. Tlačna čvrstoća je ispitana nakon 7, 28 i 90 dana. Utjecajni parametri na 28-dnevnu tlačnu čvrstoću vrednovani su faktoriskim eksperimentom i svrstavanjem u razrede čvrstoće. Dobiveni rezultati opravdavaju upotrebu otpadnih i recikliranih materijala u kolničkim konstrukcijama.

Ključne riječi:
cementna stabilizacija, leteći pepeo, reciklirani asfaltni kolnik, tlačna čvrstoća

1. Introduction

Natural stone aggregate and cement have been used for many years as basic components of pavement stabilization layers. Cement stabilization layers are realised in order to increase the bearing capacity of pavement structures [1, 2]. Cement stabilizations can be equally successfully when placed under asphalt pavement and under the cement concrete pavement, influencing reduction of upward movement of fine particles from lower layers. The properties of the stabilized layer directly depend on the type and amount of binder in the mixture. A higher binder content entails a higher water content, and together they affect reduction in the volume of voids within the stabilized mixture (Figure 1) [3]. This ensures better realization of dense structure in the stabilized mixture compaction process, which determines physical and mechanical properties of cement-stabilized pavements. Cement-stabilized materials are a specific example of concrete composites that must provide adequate compressive strength while at the same time being flexible, which is a self-contradiction. For this reason, it is necessary to limit the quantity of cement and to accurately define the cement class in mixtures [4]. In stabilized cement mixtures, it is not recommended to use cement classes higher than 32.5, precisely because of restrictions regarding the stiffness of cement-stabilized materials.
Apart from being essential for the hydration process of cement, the main goal of adding water to stabilized mixtures is to ensure good placement into the pavement structure. This operation is carried out by intensive compaction processes in cement-stabilized mixtures, which differs from processes used in conventional concrete mixtures.
Due to the global need for environmental protection through reduction of waste landfills and preservation of natural raw materials, numerous alternative materials have been introduced in the road construction industry worldwide in recent years. Among alternative materials, the possibility of utilizing fly ash from thermal power plants (FA), and the reclaimed asphalt pavement aggregate (RAP), has been attracting quite a lot of attention. Fly ash can successfully replace a part of cement, while RAP is used as a substitute material for natural aggregate in cement stabilization.
The issue with large quantities of fly ash found at landfills all over the world is not a new one, i.e., it has been present since the start of electricity production in thermal power plants. According to ECOBA (European Coal Combustion Products Association) statistics on the production and utilisation of coal combustion products (CCPs) for 2016, the total quantity of CCPs in power plants amounted to 40 million tonnes in member countries [5]. Estimates on CCPs in Europe are given in Table 1. Proportions of various types of CCPs is shown graphically in the same table. The world's largest producers of CCPs are China, India, and the USA. China is the largest consumer of coal in the world. Coal fly ash (CFA) is currently one of the most represented solid waste materials in China. In 2018, the annual output of CFA in China exceeded 550 million tons and, owing to insufficient utilization, the total accumulated quantity of CFA has exceeded 3 billion tons [6]. India produced approximately 180 million tons of fly-ash in 2017 [7]. As reported by the American Coal Ash Association, the annual production of CCPs in 2018 amounted to more than 100 million tons, while the total production of FA was more than 35 million tons [8].
Statistical data show that about 7 million tons of fly ash and slag are produced annually in thermal power plants in Serbia, with the production ratio of 9:1. Only 3 % of this amount is used in cement production [9]. The total amount of fly ash deposited in landfills, which occupy an area of approximately 1700 ha, is estimated at about 300 million tons. This huge quantity of fly ash and various possibilities of its utilization make fly ash the most widely used waste material in the construction industry of Serbia [10].
According to *IEA (2019) World Energy Outlook (All rights reserved)* [11], there are three scenarios relating to the global coal demand in the period until 2040. The Current Policies Scenario (CPS) is based on the ongoing world electricity demand, especially in developing Asian countries. The Stated Policies Scenario (STEPS) shows the intention to "hold up a mirror" to the plans and ambitions announced by policy makers without trying to anticipate how these plans might change in the future. The Sustainable Development Scenario (SDS) provides a strategic pathway to meet global climate, air quality and energy access goals in full. The global coal demand for the 2018-2040 period can be estimated, according to these three scenarios, as shown in Figure 2. If CPS or STEPS prevail, the global coal demand will remain at the same level or will even rise. In that case, the amount of CFA generation will increase. The future of coal is heavily dependent on the breadth and stringency of environmental policies across the world.

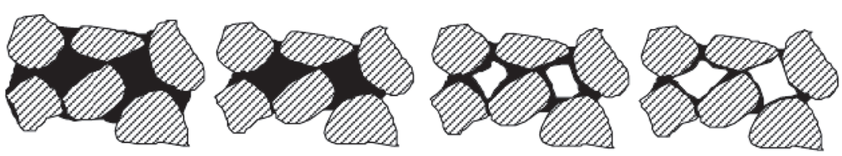
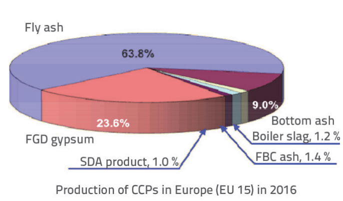


Figure 1. Voids in stabilized mixtures due to reduction of cement paste content [3]

Table 1. Estimates on CCP production in 2016 in Europe [4]

	EU 15 countries - ECOBA	EU 28 countries	Europe
Production	(milion tons)		
CCP total	40.33	> 105	> 145
Ashes	30.42	> 88	> 124
Desulph. products	9.92	> 21	> 21



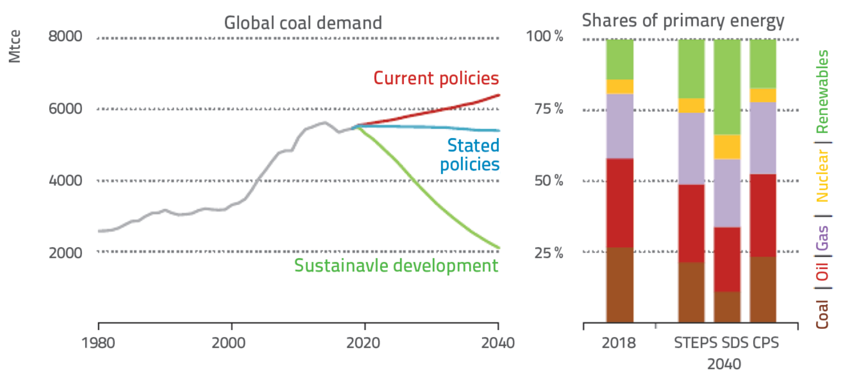


Figure 2. Global coal demand by scenario, Source: IEA (2019) World Energy Outlook (All rights reserved) [11]

- use of locally available materials,
- better resistance to sulphate attack and alkali silica reaction,
- lower cost,
- autogenous healing,
- lower energy consumption,
- reduction of CO_2 emissions when compared to cement production,
- suitability for use with recycled materials and
- placing is possible with conventional equipment.

Fly ash with adequate pozzolanic properties [4] and possibilities to increase strength over time can be successfully applied as a binding material in various concrete composites [12]. Fly ash has found its place in the construction of cement-stabilized pavement structures, where it can be used as a stabilizer [13]. Calcareous fly ash, classified according to EN 14227-4, can be used as a binder on its own, while siliceous fly ash requires the use of an activator such as cement or lime (to stimulate pozzolanic reaction). The fact that fly ash is a material that can be used in stabilized pavement structures in its original form and without any processing justifies its application.

The possibility and justification of using fly ash (FA) as an industrial by-product in pavement-structure stabilization layers is investigated in papers [14-16]. In [14], the authors investigated the possibilities of replacing cement binder with 25, 50, and 75 % of FA for the stabilization of unbound bearing layers made of stone materials. The analysis of compressive strength values obtained in this study showed that best results were obtained for the mixtures containing 25 % of FA, and this amount was recommended as an optimum cement replacement. A decrease of the 28-day compressive strength value was observed with higher proportions of FA (50 % and 75 %). Therefore, it is necessary to monitor strength changes after 28 days, because mechanical properties significantly improve with an increase in stabilization time. Also, low early-age strengths of cement-stabilized mixtures containing fly ash should be taken into account when designing such pavement structures, as they might exceed certain specification limits [16]. The fact that the early-age strengths of cement-stabilized materials containing fly ash are lower than those of cement mixtures is compensated by the use of Portland cement with higher early-age strengths (R cements). This is of great importance on the construction site, since the hardening time of stabilized material is of great significance in road construction, and it affects the overall progress of the works. FA se jednako tako uspješno može FA can also be successfully applied in the stabilization of sand [15] and fine-grained soil materials [9]. In these studies, the authors confirm that FA can be used alone or in combination with cement as an activator. Along with the aforementioned, some additional benefits of using fly ash in the cement-stabilized pavements are [17]:

During the service life of roadways, the ride quality gradually decreases due to various types of damage appearing in the asphalt pavement structure [18]. One of better options for improving road quality is to build new road using materials from the existing pavement structure. Reclaimed asphalt pavement (RAP) is a material formed during the process of crushing damaged and old asphalt pavement. This process can be performed either in plant or in situ. Among other applications, RAP can be used for the construction of cement stabilization for pavement structures [19]. Cold in-place recycling is generally applied if recycling is done in situ. All asphalt layers can be recycled successfully. By its composition, it is a distinct and heterogeneous material with various content of natural stone aggregate and old hardened bitumen (Figure 3) [20]. Physical and mechanical properties of cement stabilization depend on the content ratio of these two materials in the recycled aggregate. Aggregate particles containing more stone material are considered to have better properties.

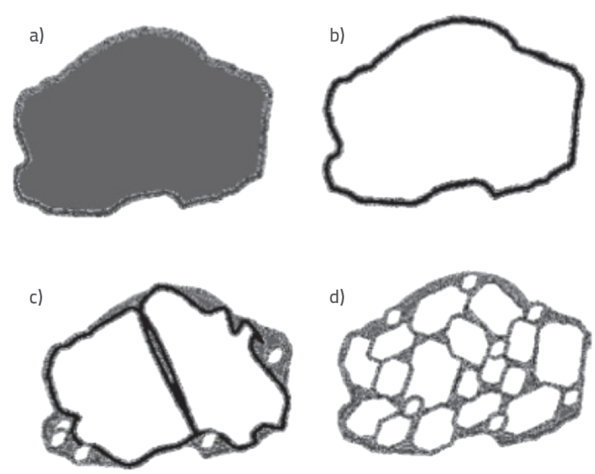


Figure 3. Non-homogeneity of RAP particle composition: a) bitumen aggregate particle, b) stone aggregate particle, c) particle with higher content of stone material, d) particle containing fine aggregate and greater amount of bitumen binder [20]

On the global level, RAP is mainly used for the production of new asphalt mixtures and in the construction of stabilized layers of pavement structures [21]. During the stabilization process, the old asphalt pavement is crushed and blended with hydraulic binder on the site (Figure 4) using special recycling machines [22]. The newly formed crushed aggregate and hydraulic binder mixture makes up a stabilized layer of pavement structure with the help of intensive compacting process, and it represents a basis for new asphalt layers. The above-mentioned application of RAP is the most favourable procedure in road reconstruction activities, when analysed from the economic aspect, the aspect of energy consumption or reduction of CO_2 emissions [23, 24].

Figure 4. Cement stabilization of RAP using cold in-place recycling technology

Characteristics of cement stabilizations (CS) containing recycled asphalt pavement (RAP) generated in the process of cold asphalt recycling are analysed in detail in papers [25-33]. The level of substitution of natural or crushed stone aggregate with RAP can vary to a great extent (0-100 %). The commonly used amount of cement is up to 6 % by weight [25-27, 29-32]. The authors [25-28] found that the optimum moisture content (OMC) in CS usually ranges between 5 and 9 %. A decrease in maximum dry density (MDD) and compressive strength of cement stabilization can be observed in the case of an increase in RAP content [25-32]. The undivided conclusion of the authors [26, 28, 30, 32] is that a complete replacement of stone aggregate with RAP leads to unsatisfactory compressive strength of CS, except in the cases of stabilization involving local roads [29]. Stone aggregate can be successfully replaced with RAP in the proportion of up to 60 % [31, 32]. The use of RAP offers significant benefits from the economic [25], environmental, technical, and technological aspects [26].

Some authors have analysed the possibility of stabilizing RAP and stone aggregate with FA, as a single binder [34, 38]. The share of FA in stabilized mixtures ranged from 10 to 18 % [34-36], while in [37, 38] the amount of FA was raised up to 30 % and 40 %, respectively. It was observed that an optimum moisture content (OMC) of stabilizing mixtures increases with a higher participation of RAP and FA [34, 35]. The authors [34-36] consider that compressive strength rises with an increase in FA content. The highest compressive strength was achieved with approximately 15 % of FA [34, 37]. In paper [38], the authors conclude that stabilizations with 100 % of RAP have unsatisfactory mechanical characteristics, because RAP exhibits a poor bond strength between aged bitumen and stone aggregate. Therefore, they advise limited replacement of stone aggregate with RAP or combining FA with cement. Most of the studies available in the literature deal with the replacement of natural aggregate with RAP at various proportions such as 90:10, 80:20, until 50:50 percent by weight. Higher RAP replacements are not encouraged by several state departments of transportation (DOTs) in the United States due to a lack of research studies on the use of higher proportions of RAP [38]. By analysing the cost of load-bearing layers of pavement structures in [36], it was established that the cost of these layers with unbound natural aggregate is approximately the same as that of RAP stabilization with FA, noting that the latter solution has better characteristics.

Since RAP and fly ash are practically free of charge, economic benefits of their application are even more pronounced. Their application would also provide a reduction in total construction costs while simultaneously the main goal would be achieved: requirements for the new pavement structure quality and traffic conditions would not be compromised. Using fly ash and RAP to a greater extent than is presently the case would allow fulfilment of numerous environmental requirements, thus further promoting sustainable construction and waste management. Moreover, the total costs are even lower if the old asphalt pavement is recycled on site and built into a new pavement structure using the cold recycling process.

The analysis of aforementioned research results allows for the observation that the investigation of simultaneous usage of combined materials in cement stabilizations, such as FA + cement and RAP + natural aggregate, is still lacking. Therefore, the authors decided to examine the possibility of applying the mentioned waste materials in cement-stabilized pavement structures based on compressive strength results obtained by lab-scale experiments.

The research presented in this paper demonstrates the influence of FA and RAP, when used as supplements to cement and natural aggregate, on the compressive strength of cement-stabilized pavements. The impact of different amounts of FA and RAP used in cement stabilizations on their 28-day compressive strength values was evaluated by full factorial design.

Bearing in mind the fact that the construction and reconstruction of roads require significant quantities of natural raw materials, the use of recycled and waste materials in cement stabilizations is considered to be both beneficial and reasonable.

2. Experimental research

Experimental tests in laboratory were conducted on 12 different mixtures of chemically stabilized blended aggregate. This investigation was realized in the following four stages:

- characterization of used component materials
- determination of optimum moisture content (OMC) and maximum dry density by Proctor compaction test (MDD)
- preparation and curing of specimens for compressive strength testing
- determination of unconfined compressive strength (UCS) at different ages.

A total of 108 cylindrical specimens were prepared for the compressive strength testing.

Figure 5. Natural aggregate (0/16 mm)

Figure 6. RAP aggregate (0/16 mm)

Figure 7. Mixture containing natural aggregate and RAP with content ratio of 70 %SG : 30 %RAP

Table 2. Geometrical, physical, mechanical and chemical properties of natural and recycled aggregates

Property	Testing method	Natural aggregate	Reclaimed asphalt pavement aggregate	Category (EN 13242)
Particle shape - shape index [%]	EN 933-4	10	11	SI_{15}
Assessment of fineness - Sand equivalent test [%]	EN 933-8	81	85	SE_{65}
Loose bulk density [kg/m³]	EN 1097-3	1770	1430	-
Compacted bulk density [kg/m³]	EN 1097-3	1870	1540	-
Water absorption [%]	EN 1097-6	1.0	0.77	$WA_{24}1$
Resistance to fragmentation - Los Angeles [%]	EN 1097-2	27	-	LA_{30}
Lightweight contaminators [%]	EN 1744-1	0.0	0.3	-
Presence of humus [%]	EN 1744-1	0.0	0.0	0 %

2.1. Component materials

The following component materials were used in the experimental study:
- natural river aggregate: "all-in" aggregate, sandy gravel (SG), (Figure 5)
- reclaimed asphalt pavement: "all-in" recycled aggregate (RAP), (Figure 6)
- Portland cement (PC)
- coal fly ash (FA)
- water.

The natural aggregate originated from the Danube basin. RAP was obtained by scraping the damaged surface asphalt coarse at the location of Iriski Venac, on the state road IB Novi Sad - Ruma. After scraping and crushing, RAP was deposited on a landfill. By sieving the RAP from the landfill, it was determined that 100 % of recycled aggregate passes through a 16mm sieve. The maximum grain size of both aggregates was D = 16 mm. Basic properties of SG and RAP are given in Table 2.

It is important to pay attention to temperature during the RAP drying process. Namely, at high temperatures (approximately 105 °C for drying stone materials), bitumen melts and aggregate particles stick together, changing granulometric composition of the aggregate. Therefore, the drying process was carried out over a longer period of time (>24 h) at lower temperatures (approximately 50 °C).

The percentage of bitumen in RAP was 3.8 % (category $Ra_{5,}$ according to EN 13242). It can be concluded rom Table 2 that both types of aggregate satisfy the same criteria as to particle shape, assessment of fineness, water absorption, and presence of humus. RAP has lower loose bulk density and compacted bulk density due to the presence of asphalt binder.

The particle size distribution of both aggregates and their mix ratio of 70 %G : 30 %RAP (Figure 7) were determined according to EN 933-1, as shown in Figure 8. The grading curve of natural aggregate (SG) shows a certain discontinuity in the medium area of sand which is typical for "Danube" aggregate. The content of grains smaller than 4 mm (≈45 % by mass) in the total amount of aggregate is suitable for adequate compaction of the stabilized mixture.

The cement used in the research (Figure 9) was produced at Lafarge factory, Beočin (Serbia) and it was labelled as CEM II/B-M (V-L) 32.5R. Chemical composition of the chosen cement is given in Table 3. The use of cement of high early strength in the cement-stabilized materials is favourable, as fast hardening of cement-stabilized material is required, because this material must reach the required strength and bearing capacity before the asphalt layers are placed in the pavement structure.

Coal fly ash from thermal power plant "Nikola Tesla B" in Obrenovac, Serbia (Figure 10), was used as a supplementary binder material in the research. Chemical composition of the fly ash is given in Table 3. Based on these data, it can be classified as calcareous fly ash according to EN 14227-4.

Table 3. Chemical composition of CEM II/B-M (V-L) 32.5R and FA

Binder	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	CaO, free	LOI
PC	25.04	7.93	2.83	50.19	2.73	2.18	0.39	0.48	0.89	8.24
FA	50.08	18.55	5.84	11.29	1.34	2.63	0.74	1.78	-	7.16

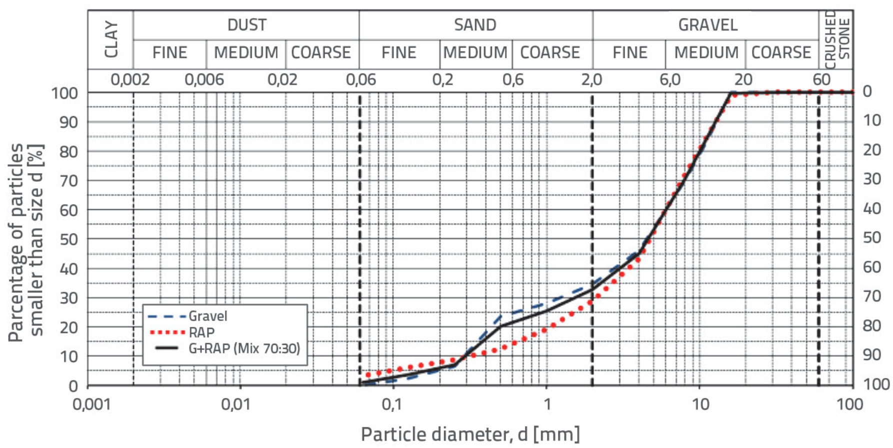


Figure 8. Particle size distribution of natural aggregate, recycled aggregate and mixture SG : RAP = 70 : 30

of authors [39] have investigated the radioactivity of fly ash (of the same origin as the fly ash used in this study) and have analysed the possibilities of its usage in construction from this aspect. Their findings have shown that the radioactivity of this fly ash is within the allowed limits, and that its application (both for road and building construction) is not harmful to human health and the environment. Tap water was used in the experimental research, which is in compliance with EN 1008.

Figure 9. Cement CEM II/B-M (V-L) 32.5R **Figure 10. Coal fly ash**

Since fly ash usually contains radioactive elements (such as uranium, radium, thorium, etc.), it is necessary to pay attention to radioactivity limitations when analysing its application. A group

2.2. Composition of stabilized mixtures

The mix design was based on the following proportions:
- Total amount of binder (PC+FA): 4 % or 6 %
- Replacement of SG with RAP: 0 % or 30 %
- Replacement of PC with FA: 0 %, 20 % and 40 % .

These proportions were defined based on the analysis of literature available in this field, and according to practical data obtained from the construction site.

By varying the types and quantities of component materials, a total of twelve different stabilized mixtures were designed (Figure 11).

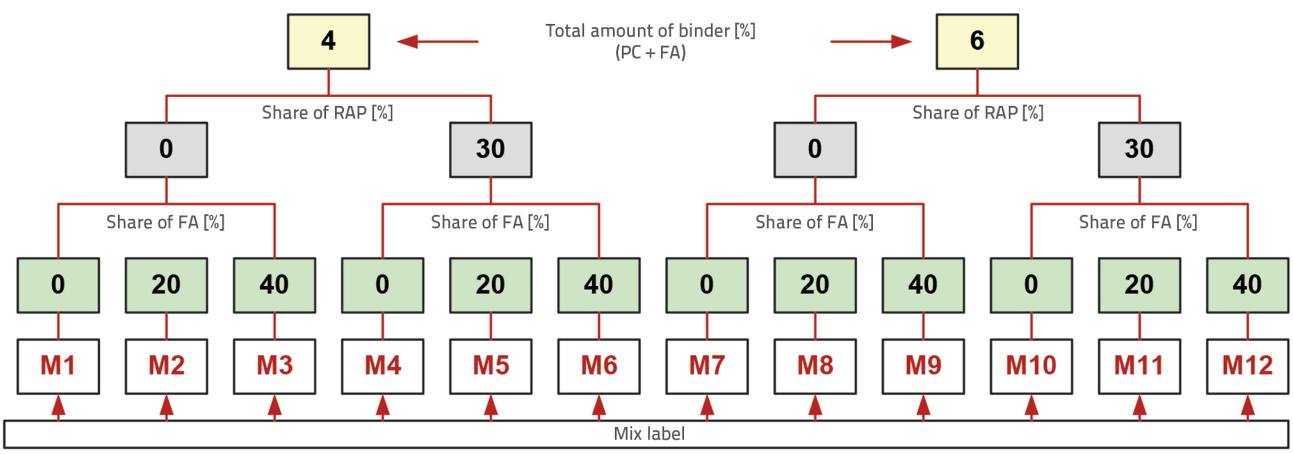


Figure 11. Composition and labels of stabilized mixtures

3. Maximum dry density and optimum moisture content

Proctor compaction test is a process in which stabilized mixtures are intensively compacted and their maximum dry density (MDD) and optimum moisture content (OMC) are defined. This test is categorised as a preliminary test of stabilized mixtures. In this experimental study, the tests were performed using metal cylindrical moulds and Proctor rammer, according to EN 13286-2. Based on the particle size of aggregate (D = 16 mm), the Standard Proctor Test was carried out using type A mould measuring d = 10 cm and h = 12 cm, and a 2.5 kg rammer. The compaction energy was 0.6 MJ/m^3. The results of the Proctor compaction test for OMC are given in Figure 12, while the results for MDD are given in Figure 13.

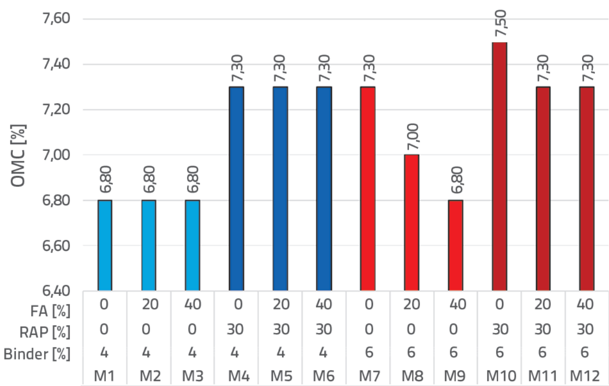


Figure 12. Optimum moisture content (OMC) of tested stabilized mixtures

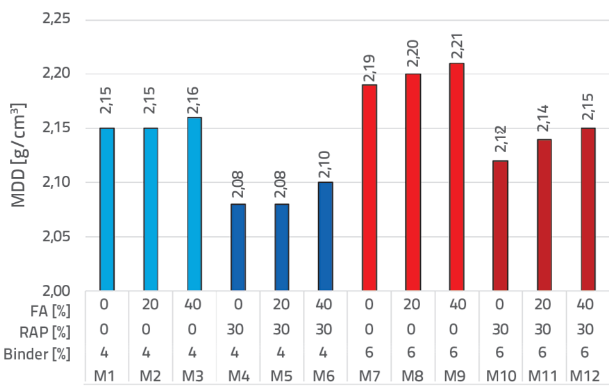


Figure 13. Maximum dry density (MDD) of tested stabilized mixtures

An optimal moisture content of tested stabilized mixtures ranges between 6.8 % and 7.5 %, while the maximum dry density is between 2.08g/cm^3 and 2.21g/cm^3. The OMC and MDD results can be analysed from three aspects: the usage of RAP, the total amount of binder, and the content of FA in the binder.

OMC values rose in the mixtures containing RAP due to a higher specific surface area and higher content of fine particles in RAP aggregate. A small growth of these values was noticed when the total binder amount was increased from 4 % to 6 %, which could be attributed to a higher content of fines in the stabilized mixtures. Fly ash did not have an effect on OMC values in stabilized mixtures with 4 % of binder, regardless of RAP content. On the other hand, in the mixtures with 6 % of binder, a decrease of OMC values was caused by a higher content of FA and its ability to improve workability.

The presence of RAP in stabilized mixtures reduced MDD values due to a lower density of RAP. With an increase in the total amount of binder, MDD rose because the inter-grain porosity of stabilized mixtures was lowered. The influence of FA content on MDD values was negligible for stabilized mixtures with 4 % of total binder, whereas its content caused a slight increase of MDD values in stabilized mixtures with 6 % of total binder. This phenomenon is likely to be connected to the fact that FA requires less water than PC and it has a better packing effect.

During the Proctor compaction test, water bleeding was noticed at the joint of the mould and the metal base plate. It was caused by a lack of finest aggregate particles during intensive compaction of stabilized mixtures, and it occurred before the OMC was achieved for the tested mixtures (Figure 14). The water bleeding rate of all mixtures was <0.3 %. That was the reason why the mould and rammer (A) continued to be used in the Proctor compaction test of stabilized mixtures, according to EN 13286-2.

Figure 14. Water bleeding at the bottom of the mould during compaction process

4. Compressive strength

After determining the OMC value for each stabilized mixture type by the Proctor compaction test (Figure 12), strength specimens were prepared with the amount of water defined according to EN 13286-50. Specimens for testing compressive strength were cylinders measuring 100 mm in diameter and 120 mm in height. They were prepared using Proctor moulds and compaction procedure according to EN 13286-2 (Figure 15). After demoulding, strength specimens were cured in a climate chamber at a temperature of (20±2)^{0}C and a relative humidity of 90 %, until the age required for testing was reached.

Compressive strength is obtained by the uniaxial unconfined compression test, conforming to EN 13286-41, at the ages of 7, 28, and 90 days. According to the characteristic failure type given in EN 13286-41, all tested specimens had satisfactory failure

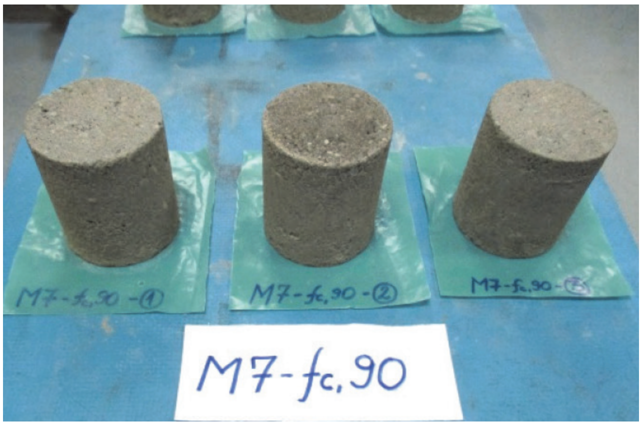


Figure 15. Appearance of hardened stabilized specimens after 90 days of curing

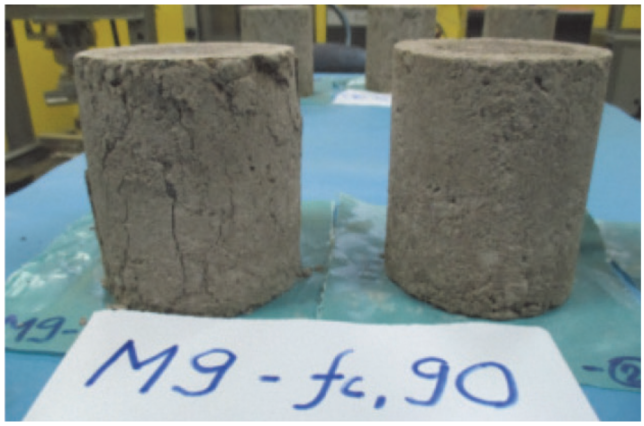


Figure 16. Appearance of stabilized specimen before (right) and after (left) compressive strength testing

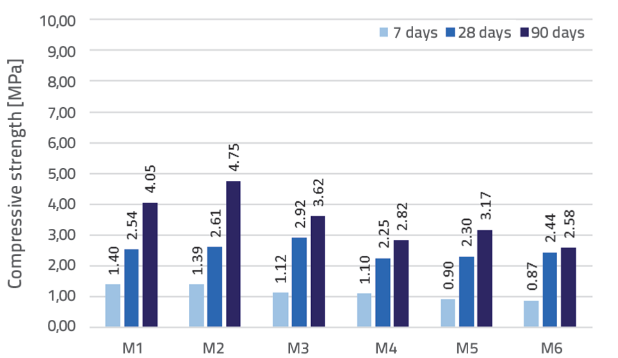


Figure 17. Compressive strengths of stabilized mixtures with 4 % binder depending on age

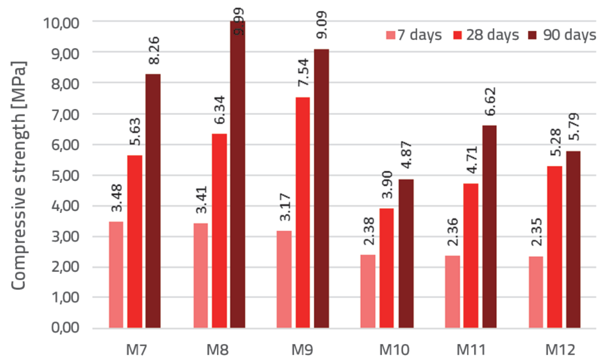


Figure 18. Compressive strengths of stabilized mixtures with 6 % binder depending on age

mode, i.e. mode 4 with vertical parallel cracks (Figure 16). The compressive strength results are shown in charts (Figure 17 and 18) as mean values of three individual results for each of twelve stabilized mixtures.

Comparing an increase in compressive strength for periods from 7 to 28 days, it can be observed that this increase was most pronounced in the mixtures with the highest content of fly ash (M3, M6, M9, M12) and it ranged from 125 % for M12 to 180 % for M6. This is even more important when considering that an increase in FA amount influenced a decrease in the 7-day compressive strength and an increase in the 28-day strength, for all mixture types (Figure 17 and Figure 18). Our results confirm the hypothesis that fly ash develops a pozzolanic reaction slowly and achieves strength at later ages [16]. It is also of interest to compare an increase in strength of the mixtures from 28 to 90 days. The lowest strength increase is characteristic for the mixtures with 40 % of FA (M3, M6, M9 and M12), while the highest strength increase was observed in the mixtures with 20 % of FA (M2, M5, M8 and M11). Although the application of RAP in the mixtures reduced compressive strength, this reduction was not sufficient to exclude RAP from the composition of stabilized mixtures. The difference in strength of the mixtures with and without RAP can be compensated by the use of fly ash at a replacement level of 40 % (comparing M1- M6, or M7-M12, at 28 days).

It is interesting to note that although the 28-day compressive strengths were constantly increasing with a rise in fly ash content in mixtures (for both total amounts of binder), this was not the case with the 90-day strengths. They exhibited lower values in the mixtures with 40 % of fly ash. This fact could be considered positive regarding the rigidity limitations of stabilisation layers in road pavements.

The compressive strength of cement-stabilized mixtures is the most important mechanical property of this type of so-called *weak* concretes, and the requirements for the quality of cement-stabilized layers are defined based on this property. These requirements are not uniform and they vary by country. Additionally, determination of the required compressive strength is also affected by the road type and traffic load. The European standard EN 14227-1 classifies hydraulically bound mixes into strength classes, similar to concrete classes [40]. In accordance with this standard, tested mixtures are classified in certain strength classes (Table 4). The classification into the given classes was done on the basis of the 28-day compressive strength obtained on cylindrical specimens. If cylinders with slenderness ratios other than 1 or 2 are used in strength class assessment, the correlation with cylinders of either slenderness ratio 1 or 2 shall be established before use (EN 14227-1). In our research, the slenderness ratio was 1.2, so we calculated the criteria (Table 4, column 4) to assess the strength class.

This analysis clearly shows that the share of binder in tested mixtures has the greatest influence on strength class. The difference between these two groups of mixtures varies between two and

Table 4. Strength class of stabilized mixtures tested according to EN 14227-1

Composition			Mixture type	Compressive strength [MPa]	EN 14227-1	
					Criteria [MPa]	Strength class
1			2	3	4	5
4 % binder	0 % RAP	0 % FA	**M1**	2.54	≥1.90	**C1.5/2**
		20 % FA	**M2**	2.61	≥1.90	**C1.5/2**
		40 % FA	**M3**	2.93	≥2.86	**C2.3/3**
	30 % RAP	0 % FA	**M4**	2.25	≥1.90	**C1.5/2**
		20 % FA	**M5**	2.30	≥1.90	**C1.5/2**
		40 % FA	**M6**	2.44	≥1.90	**C1.5/2**
6 % binder	0 % RAP	0 % FA	**M7**	5.64	≥4.80	**C4/5**
		20 % FA	**M8**	6.34	≥5.80	**C5/6**
		40 % FA	**M9**	7.54	≥5.80	**C5/6**
	30 % RAP	0 % FA	**M10**	3.90	≥3.80	**C3/4**
		20 % FA	**M11**	4.71	≥3.80	**C3/4**
		40 % FA	**M12**	5.27	≥4.80	**C4/5**

four strength classes. In the group with 4 % of binder, five out of six mixtures belong to the same strength class (C1,5/2), which means that the influence of both varied parameters, RAP and FA, on strength class is negligible. On the other hand, the participation of RAP in the group of mixtures with 6 % of binder has a negative effect, while the share of FA has a positive effect on the strength class. It is clear that the combination of different proportions of materials used in this research can generate a very wide strength class range of cement stabilizations. This conclusion enables substitution of natural aggregate and Portland cement with RAP and FA in cement stabilization layers for various road types and traffic loads.

It is important to note that the compressive strength testing and analysis results relate exclusively to the fly ash used in this research (from thermal power plant "Nikola Tesla B"). Therefore, when preparing a composition design for stabilized mixtures, it is necessary to carry out a chemical analysis of fly ash, followed by preliminary determination of Proctor test and compressive strength values. Chemical composition of fly ash of various origins is often inconsistent, which is why conducting a chemical analysis that determines the possibility of using it in concrete composites to the greatest extent possible is quite important. Properties of coal, as a raw material used for its production, and the process of its combustion in the boiler, are the key factors affecting fly ash quality [4].

5. Analysis of compressive strength test results by full factorial design

A full factorial design was conducted to evaluate simultaneous influence of varied parameters on the 28-day compressive strength of cement stabilizations, and to determine which of the analysed factors has the greatest effect [41-43]. This type of statistical analysis allows testing the hypothesis of possible relationships between the compressive strength of the tested cement stabilizations and the varied influencing factors. The relative magnitude of impact of varied parameters can also be defined by factorial analysis. Based on their influence on the compressive strength value, the simplest analytical relation "compressive strength of cement stabilization - influential parameters" can be formulated.

The factorial design was structured as 2^3, which included three variable factors and two levels of consideration.

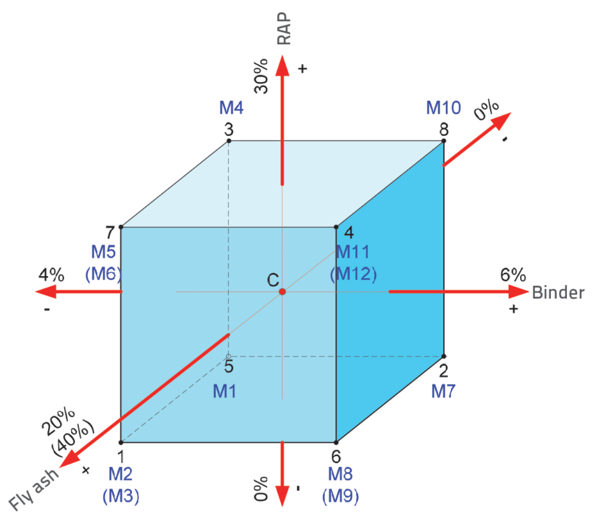
In this experimental study of cement stabilizations, the proportion of binder and RAP was varied at 2 levels (4 % and 6 % for binder, and 0 % and 30 % for RAP), while the proportion of FA was varied at 3 levels (0 %, 20 %, and 40 %). The factorial design 2^3 was chosen since there are three variables, two of which were varied at two levels. To take advantage of the selected factorial design structure, two factorial analyses were performed: in the

Table 5. Description of influencing factors and possible levels of their consideration

Influencing factors		Level of consideration (x_i - coded dimensionless valuet)			
		Lower level		Upper level	
Label	Description	Value	Parameter description	Value	Parameter description
Z_1	Količina veziva	**-1**	4 %	**+1**	6 %
Z_2	Udio RAP-a	**-1**	0 %	**+1**	30 %
Z_3	Udio FA-a	**-1**	0 %	**+1**	20 % (40 %)

Table 6. Values of dimensionless coordinates "x_i" and their corresponding products

N	Type of cement stabilization	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$
1	M2 (M3)	-1	-1	+1	+1	-1	-1	+1
2	M7	+1	-1	-1	-1	-1	+1	+1
3	M4	-1	+1	-1	-1	+1	-1	+1
4	M11 (M12)	+1	+1	+1	+1	+1	+1	+1
5	M1	-1	-1	-1	+1	+1	+1	-1
6	M8 (M9)	+1	-1	+1	-1	+1	-1	-1
7	M5 (M6)	-1	+1	+1	-1	-1	+1	-1
8	M10	+1	+1	-1	+1	-1	-1	-1



Vertex	Z_1	Z_2	Z_3
1	4 %	0 %	20 % (40 %)
2	6 %	0 %	0 % (0 %)
3	4 %	30 %	0 % (0 %)
4	6 %	30 %	20 % (40 %)
5	4 %	0 %	0 % (0 %)
6	6 %	0 %	20 % (40 %)
7	4 %	30 %	20 % (40 %)
8	6 %	30 %	0 % (0 %)

Figure 19. Graphical model of 2³ factorial design

first one, the share of FA was varied at two levels (0 % and 20 %), whereas the levels 0 % and 40 % were selected in the second one. Experimental compressive-strength values of cement stabilizations at the age of 28 days were used in these analyses. Basic data for factorial analysis, which included three varied factors and two levels of consideration, are given in Table 5. The values in parentheses were used in the second analysis.

Graphical representation of these data, as well as the scope of factorial analyses, are shown in Figure 19.

Each vertex of the imagined model represents one combination of influencing factors, which gives 8 different types of cement stabilizations with a maximum amount of 20 % of FA, and additional 4 cement stabilizations with a maximum amount of 40 % of FA for the second factorial analysis (values in parentheses).

The centre of the factorial experiment (cube) can be physically interpreted as cement stabilization, which is a mean value between cement stabilizations made with 4 % of binder and 6 % of binder, 0 % of RAP and 30 % of RAP and 0 % of FA and 20 % (40 %) of FA. Thus, the centre of the factorial experiment represents the imagined cement stabilization with 5 % of binder, 15 % of RAP, and 10 % of FA (20 % of FA in the second factorial analysis).

In the factorial design, the functional relation between the analyzed property and the varied parameters is approximated by the following polynomial:

$$f(Z_1, Z_2, Z_3) = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3 \quad (1)$$

All values of coded dimensionless coordinates "x_i", and the values of their corresponding products, which are necessary for the calculation of the polynomial coefficients, are given in Table 6.

The coefficients of the polynomial are determined by the following expressions:

$$b_0 = \frac{1}{N}\sum_{j=1}^{N} y_j \quad (2)$$

$$b_i = \frac{1}{N}\sum_{j=1}^{N} x_{ij}y_j \text{ (i = 1, 2 i 3)} \quad (3)$$

$$b_{km} = \frac{1}{N}\sum_{j=1}^{N} x_{kj}x_{mj}y_j \text{ (k = 1, 2 i 3; m = 1, 2 i 3)} \quad (4)$$

$$b_{123} = \frac{1}{N}\sum_{j=1}^{N} x_{1j}x_{2j}x_{3j}y_j \quad (5)$$

Table 7. Polynomial coefficients of the relation"$f_{c,28} = f_{c,28}(Z_1, Z_2, Z_3)$"

Amount of FA [%]	Polynomial coefficients							
	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{123}
20	3.787	1.360	-0.496	0.205	-0.345	0.176	0.011	0.018
40	4.064	1.523	-0.598	0.482	-0.404	0.339	-0.091	-0.042

where "y_j" is an average value of individual test results of the 28-day compressive strength of cement stabilization for a certain combination of influential parameters, or for a certain type of cement stabilization.
The coefficients of polynomial (1) were calculated based on expressions (2) - (5) and experimental values of 28-day compressive strengths of cement stabilizations.
The analytical relation between the compressive strength of cement stabilization and the simultaneous influence of all three varied parameters, for the maximum amount of FA = 20 %, is:

$$f_{c,28,20\,\%FA} = 3.787+1.360x_1-0.496x_2+0.205x_3-0.345x_1x_2+0.176x_1x_3+0.011x_2x_3+0.018x_1x_2x_3 \quad (6)$$

The same analytical relation for the maximum amount of FA = 40 % is:

$$f_{c,28,40\,\%FA} = 4.064+1.523x_1-0.598x_2+0.482x_3-0.404x_1x_2+0.339x_1x_3-0.091x_2x_3-0.042x_1x_2x_3 \quad (7)$$

Compressive strengths of cement stabilizations, calculated by expressions (6) and (7), were identical to the experimental values, and so it was not necessary to test adequacy of the mathematical model. In order to define the influence of the varied parameters, the values of the polynomial coefficients for the analysed amounts of FA are shown in Table 7. The coefficients of polynomials define a certain type of influence, i.e. they have the following physical meaning:

- b_0 - defines an average compressive strength of all tested cement stabilizations (centre of the cube)
- b_1 - defines influence of the total amount of binder
- b_2 - defines influence of the share of RAP
- b_3 - defines the share of FA
- b_{12} - defines an additional impact due to interaction between the total amount of binder and the share of RAP
- b_{13} - defines an additional impact due to interaction between the total amount of binder and the share of FA
- b_{23} - defines an additional impact due to interaction between the share of RAP and the share of FA
- b_{123} - defines an additional impact due to interaction between the total amount of binder, the share of RAP, and the share of FA

The sign "+" in front of each coefficient of the polynomial, after multiplying it with the coded dimensionless coordinate "x_i", indicates a positive influence on the compressive strength of cement stabilization, while sign "-" shows a negative influence. The absolute value of the polynomial coefficient shows the influence of the varied factor on the compressive strength value. The following conclusions were made based on the analysis of main polynomial terms (polynomial coefficients from Table 7 multiplied with coded dimensionless coordinates "xi" from Table 6):

- Term "b_1x_1": The amount of binder has the greatest influence on the compressive strength of cement stabilizations. An average value of the coefficient "b_1" for both analyzed amounts of FA (20 % or 40 %) is +1.43, which means that the usage of larger amount of binder (6 %) causes an increase of 2.86 MPa in compressive strength.
- Term "b_2x_2": The second largest coefficient is "b_2" and it shows the influence of the amount of RAP (0 % or 30 %) on the compressive strength of cement stabilizations. An average value for both analysed amounts of FA (20 % or 40 %) is -0.55, which means that the application of 30 % of RAP causes a reduction of approximately 1.1 MPa in compressive strength.
- Term "b_3x_3": The impact of the share of FA in the total amount of binder is defined by the coefficient "b_3". 20 % of FA increases the compressive strength by 0.41MPa, and 40 % of FA increases the strength by 0.96MPa.

It is difficult to physically explain combined effects of varied parameters through the values of additional polynomial terms: "$b_{12}x_1x_2$", "$b_{13}x_1x_3$", "$b_{23}x_2x_3$" and "$b_{123}x_1x_2x_3$". They are used for mathematical calibration of the final polynomial value.
By analysing absolute values of polynomial coefficients, it was concluded that additional influences of the coefficients "b_{23}" and "b_{123}" are almost negligible. In cement stabilizations with 20 % of FA, ignoring these two coefficients results in deviations from the exact values of less than 1 %. In the case of cement stabilizations with 40 % of FA, the largest deviation is 3.4 %, i.e., 0.13 MPa. The omission of coefficients "b_{23}" and "b_{123}" from expressions 6 and 7 generates simplified expressions for the analytical determination of the compressive strength of cement stabilizations:

$$f_{c,28,20\,\%FA} = 3.787+1.360x_1-0.496x_2+0.205x_3-0.345x_1x_2+0.176x_1x_3 \quad (8)$$

$$f_{c,28,40\,\%FA} = 4.064+1.523x_1-0.598x_2+0.482x_3-0.404x_1x_2+0.339x_1x_3 \quad (9)$$

Experimental values of 28-day compressive strengths and their corresponding analytical values obtained by simplified expressions (8) and (9) are illustrated in Figures 20 and 21.

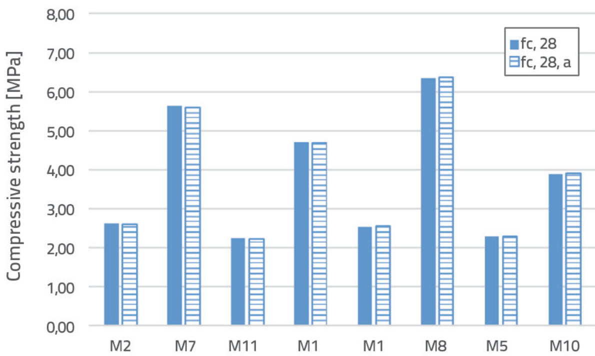


Figure 20. Experimental ($f_{c,28}$) and analytical values ($f_{c,28,a}$) of 28-day compressive strengths of cement stabilizations with 0 % and 20 % of FA

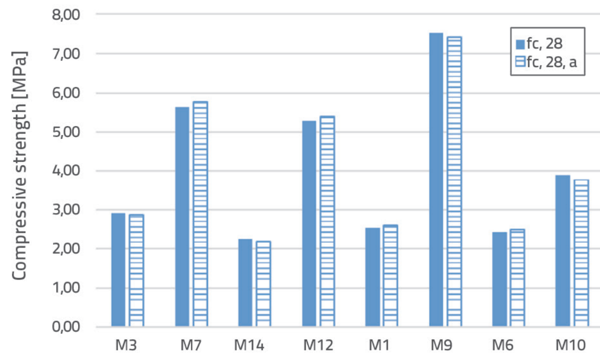


Figure 21. Experimental ($f_{c,28}$) and analytical values ($f_{c,28,a}$) of 28-day compressive strengths of cement stabilizations with 0 % and 40 % of FA

6. Conclusion

This study analyses the possibilities of using up to 30 % of reclaimed asphalt pavement as a substitute material for natural aggregate, along with fly ash replacing 20 % or 40 % of Portland cement in cement stabilizations with 4 % and 6 % of binder. The percentage of bitumen in RAP was 3.8 %, while FA was classified as calcareous fly ash according to EN 14227-4. When these two materials are combined, the beneficial effect of the application of waste and recycled materials becomes even more visible. Based on the analysis of the OMC and MDD values, the following conclusions were made:

- The presence of RAP in stabilized mixtures increases OMC values due to a higher specific surface area and a higher content of fine particles. On the other hand, fly ash does not have an effect on OMC values in stabilized mixtures with 4 % of binder, regardless of RAP content, while in the mixtures with 6 % of binder, a decrease in OMC values is caused by a higher content of FA.
- An increase in the total amount of binder in stabilized mixtures causes a rise of MDD because of a decrease in inter-grain porosity. RAP in stabilized mixtures reduces MDD values due to its lower density. The influence of FA content on MDD values is almost negligible for stabilized mixtures regardless of the total amount of binder.

The following can be concluded based on mathematical evaluation of the influence of varied parameters on the 28-day compressive strength, by full factorial design:

- The amount of binder has the greatest influence on the compressive strength of cement stabilizations. The usage of larger amount of binder (6 %) causes an average increase of 2.72 MPa in stabilizations with 20 % of FA, and an average rise of 3.04 MPa in those with 40 % of FA.
- The second largest influential factor is RAP. The application of 30 % of RAP causes a reduction of approximately 1.1 MPa in compressive strength for both cement stabilization types, regardless of FA content.
- The 20 % fly ash content increases the compressive strength by 0.41 MPa, while FA content of 40 % leads to a 0.96 MPa increase in strength.

According to EN 14227-1, cement stabilisations are classified in certain strength classes based on the 28-day compressive strength. This analysis confirms that the share of binder in cement stabilisations has the greatest influence on strength class. The difference between mixtures with 4 % or 6 % of binder varies from two to four strength classes (C1,5/2 – C5/6). In the group with 4 % of binder, the influences of RAP and FA on strength class are negligible. On the other hand, the participation of RAP in the group of mixtures with 6 % of binder has a negative effect, while the share of FA has a positive effect on strength class.

It is clear that the combination of different proportions of materials used in this research can generate a very wide strength class range of cement stabilizations. This conclusion enables the substitution of natural aggregate and Portland cement with RAP and FA in cement stabilization layers for various road types and traffic loads. The results obtained in our research justify the use of fly ash and RAP in cement-stabilized pavement structures. A more extensive use of these materials in road construction would bring considerable economic, energy efficiency, environmental, and other benefits.

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